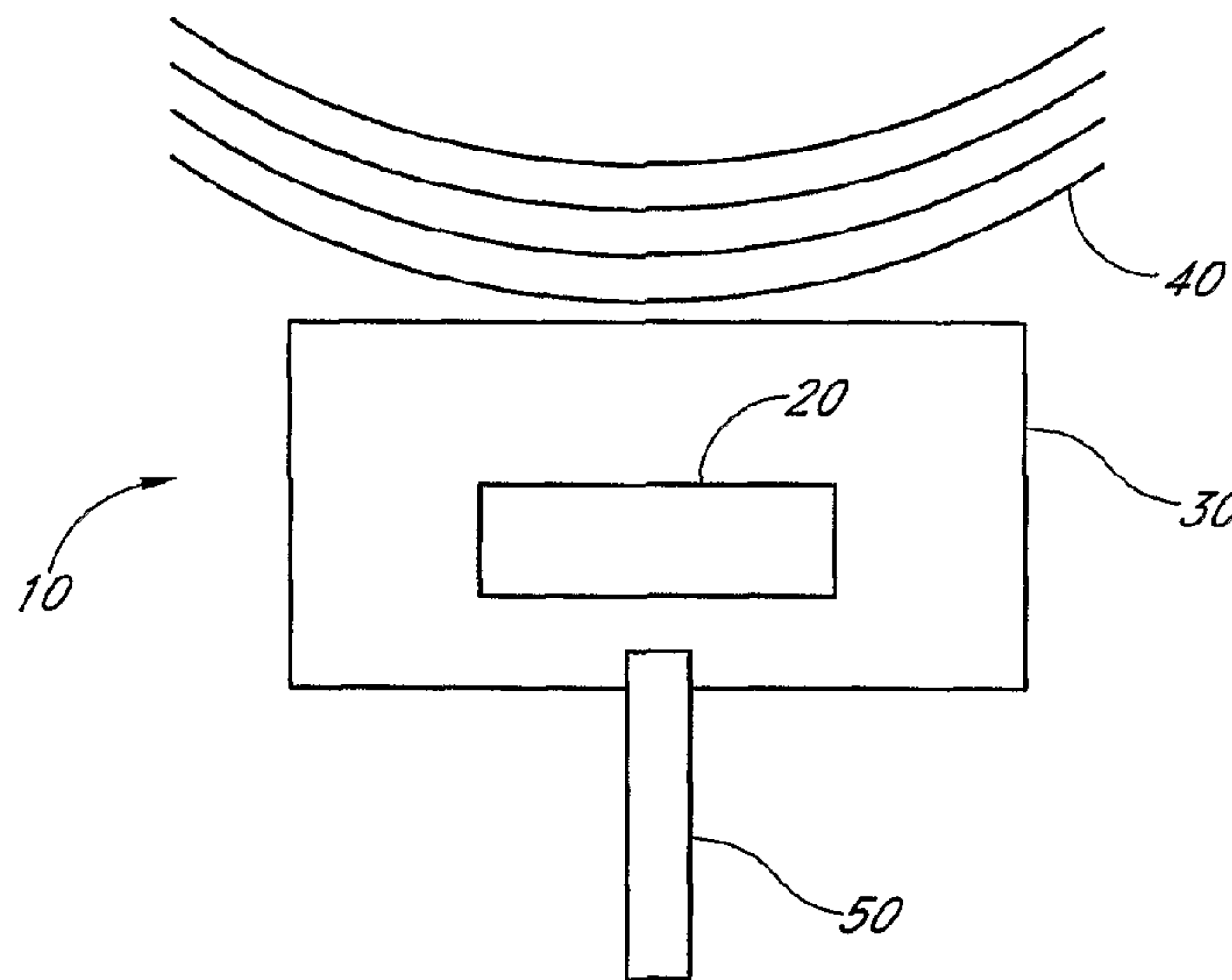




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(54) **Titre : DETECTEUR ACOUSTIQUE ET OPTIQUE COMPATIBLE AVEC DES FIBRES ET PRESENTANT UNE SENSIBILITE ELEVEE**
(54) **Title: HIGH-SENSITIVITY FIBER-COMPATIBLE OPTICAL ACOUSTIC SENSOR**



(57) **Abrégé/Abstract:**

An acoustic sensor includes at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape. The acoustic sensor further includes a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure. At least one of the resonance frequency and the resonance lineshape is responsive to acoustic waves incident upon the housing.



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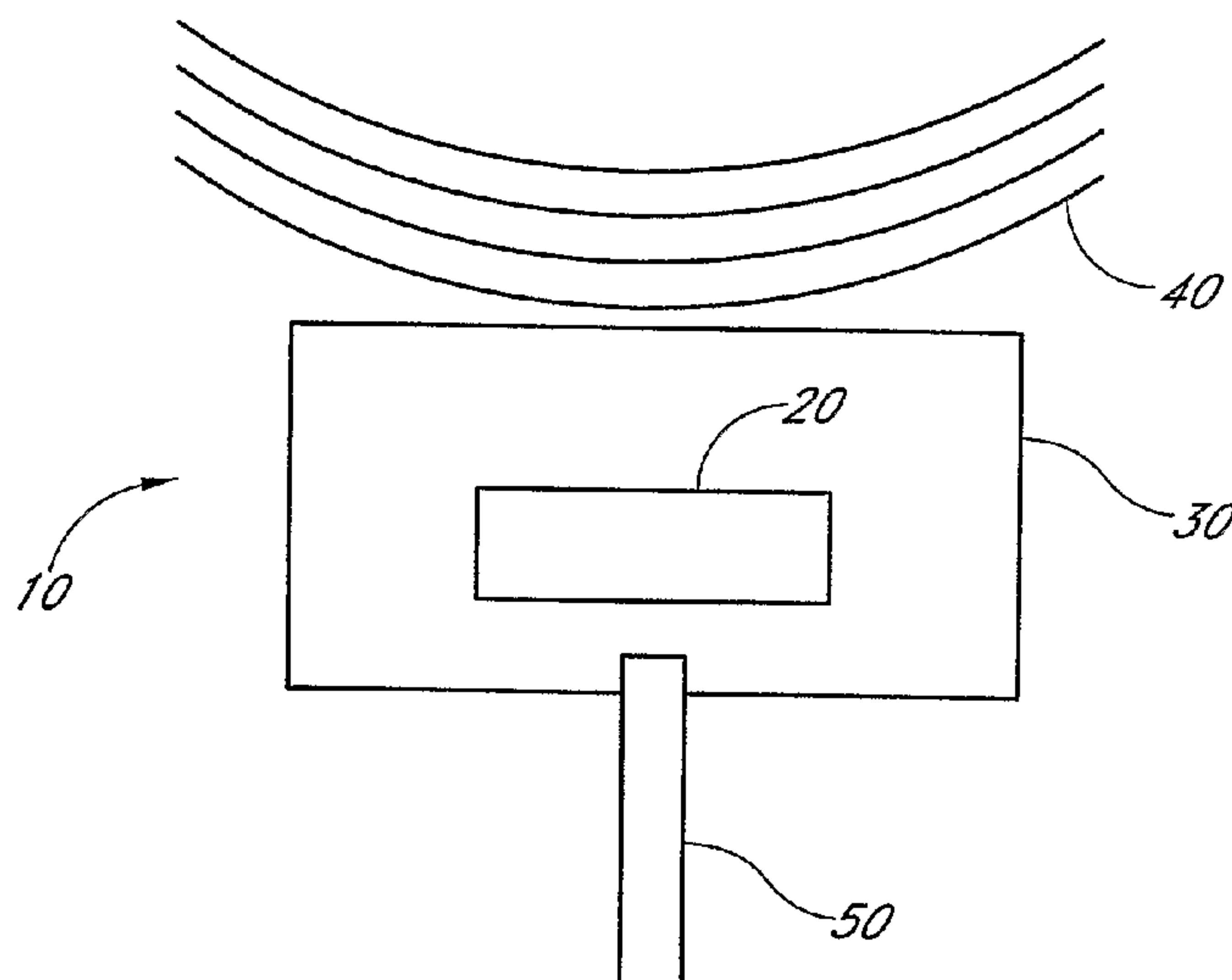
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(54) Title: HIGH-SENSITIVITY FIBER-COMPATIBLE OPTICAL ACOUSTIC SENSOR



(57) Abstract: An acoustic sensor includes at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape. The acoustic sensor further includes a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure. At least one of the resonance frequency and the resonance lineshape is responsive to acoustic waves incident upon the housing.

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PATENT

HIGH-SENSITIVITY FIBER-COMPATIBLE OPTICAL ACOUSTIC SENSOR**BACKGROUND OF THE INVENTION**Field of the Invention

[0002] This application relates generally to acoustic sensor systems, and more particularly to optical-fiber-compatible acoustic sensor systems.

Description of the Related Art

[0003] Various fiber optic sensor systems have been previously disclosed that provide acoustic pressure measurements based on the relative displacements of the two mirrors of a Fabry-Perot interferometric cavity. See, e.g., M. Yu *et al.*, “*Acoustic Measurements Using a Fiber Optic Sensor System*,” J. Intelligent Mat’l Systems and Structures, vol. 14, pages 409-414 (July 2003); K. Totsu *et al.*, “*Ultra-Miniature Fiber-Optic Pressure Sensor Using White Light Interferometry*,” J. Micromech. Microeng., vol. 15, pages 71-75 (2005); W.B. Spillman, Jr. *et al.*, “*Moving Fiber-Optic Hydrophone*,” Optics Lett., vol. 5, no. 1, pages 30-31 (January 1980); K. Kardirvel *et al.*, “*Design and Characterization of MEMS Optical Microphone for Aeroacoustic Measurement*,” 42nd AIAA Aerospace Sciences Meeting and Exhibit, 5-8 January 2004, Reno, Nevada; J.A. Bucaro *et al.*, “*Miniature, High Performance, Low-Cost Fiber Optic Microphone*,” J. Acoust. Soc. Am., vol. 118, no. 3, part 1, pages 1406-1413 (September 2005); T.K. Gangopadhyay *et al.*, “*Modeling and Analysis of an Extrinsic Fabry-Perot Interferometer Cavity*,” Appl. Optics, vol. 44, no. 16, pages 312-3196 (1 June 2005); and P.J. Kuzmenko, “*Experimental Performance of a Miniature Fabry-Perot Fiber Optic Hydrophone*,” Proceedings of 8th Optical Fiber Sensors Conference, Monterey, California, January 29-31, 1992, pages 354-357.

[0004] Photonic crystal slabs (PCSs) are photonic crystal structures having a spatially periodically varying refractive index. A PCS exhibits guided resonance optical modes that are strongly confined within the PCS, but are coupled to incident radiation

through a phase matching mechanism due to the periodically varying refractive index. These guided resonance modes are typically manifest in transmission or reflection spectra as sharp Fano lineshapes superimposed on a smoothly varying background. *See, e.g., M. Kanskar et al., "Observation of leaky slab modes in an air-bridged semiconductor waveguide with a two-dimensional photonic lattice," Appl. Phys. Lett., vol. 70, page 1438 (1997); V.N. Astratov et al., "Resonant coupling of near-infrared radiation to photonic band structure waveguides," J. Lightwave Technol., vol. 17, page 2050 (1999); and S. Fan and J.D. Joannopoulos, "Analysis of guided resonances in photonic crystal slabs," Phys. Rev. B, vol. 65, page 235112 (2002).* Such guided resonance modes have been used previously as optical filters or mirrors in light emitting diodes and lasers.

SUMMARY OF THE INVENTION

[0005] In certain embodiments, an acoustic sensor comprises at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape. The acoustic sensor further comprises a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure. At least one of the resonance frequency and the resonance lineshape is responsive to acoustic waves incident upon the housing.

[0006] In certain embodiments, a method detects acoustic waves. The method comprises providing a sensor comprising at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape. The sensor further comprises a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure. At least one of the resonance frequency and the resonance lineshape is responsive to acoustic waves incident upon the housing. The method further comprises exposing the sensor to acoustic waves. The method further comprises detecting a change of at least one of the resonance frequency and the resonance lineshape induced by the acoustic waves.

[0006a] In accordance with an aspect of the present invention there is provided an acoustic sensor comprising:

at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape, the at least one photonic crystal structure comprising at least one photonic crystal slab having a substantially planar configuration;

an optical fiber optically coupled to the at least one photonic crystal structure, wherein light emitted from the optical fiber is incident to the at least one photonic crystal structure from a direction substantially perpendicular to the at least one photonic crystal slab; and

a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure such that acoustic waves incident upon the housing induce forces applied to the at least one photonic crystal structure that change at least one of the resonance frequency and the resonance lineshape of the at least one optical resonance of the at least one photonic crystal structure.

[0006b] In accordance with a further aspect of the present invention there is provided a method of detecting acoustic waves, the method comprising:

providing a sensor comprising at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape, the at least one photonic crystal structure comprising at least one photonic crystal slab having a substantially planar configuration, the sensor further comprising a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure such that acoustic waves incident upon the housing induce forces applied to the at least one photonic crystal structure that change at least one of the resonance frequency and the resonance lineshape of the at least one optical resonance of the at least one photonic crystal structure;

exposing the sensor to acoustic waves;

irradiating the at least one photonic crystal structure with light from a direction substantially perpendicular to the at least one photonic crystal slab; and

detecting a change of at least one of the resonance frequency and the resonance lineshape induced by the acoustic waves.

[0006c] In accordance with a further aspect of the present invention there is provided an acoustic sensor comprising:

at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape, the at least one photonic crystal structure comprising at least one photonic crystal slab having a substantially planar configuration;

an optical fiber optically coupled to the at least one photonic crystal structure, wherein light emitted from the optical fiber is incident to the at least one photonic crystal

structure in a range of incidence angles within about 10 degrees from a direction substantially perpendicular to the at least one photonic crystal slab; and

a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure such that acoustic waves incident upon the housing induce forces applied to the at least one photonic crystal structure that change at least one of the resonance frequency and the resonance lineshape of the at least one optical resonance of the at least one photonic crystal structure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figure 1 schematically illustrates an example acoustic sensor compatible with certain embodiments described herein.

[0008] Figure 2A schematically illustrates an example photonic crystal slab (PCS) having a substantially square array of substantially circular holes extending completely through the slab.

[0009] Figure 2B illustrates a scanning electron microscope micrograph of portions of an example PCS.

[0010] Figure 2C schematically illustrates another example PCS having a substantially square array of substantially circular holes extending only partly through the PCS.

[0011] Figure 2D schematically illustrates another example PCS having a substantially square distribution of protrusions.

[0012] Figures 2E and 2F schematically illustrate cross-sectional views of other example PCSs having a plurality of elongated regions with a substantially one-dimensionally-periodic distribution.

[0013] Figures 3A-3C schematically illustrates an example PCS exhibiting an optical resonance in the simulated transmitted optical power spectrum for light incident in a direction substantially perpendicular to the PCS.

[0014] Figure 4 schematically illustrates the measured resonance wavelength shift for substantially perpendicularly incident light on an example PCS as a function of temperature.

[0015] Figure 5 illustrates the resonance wavelength shift for substantially perpendicularly incident light on an example PCS as a function of mechanical forces applied to the PCS.

[0016] Figure 6 schematically illustrates an experimental configuration of a 1-centimeter long PCS in proximity to an acoustic speaker.

[0017] Figures 7A and 7B schematically illustrate an example acoustic sensor having a single PCS.

[0018] Figure 8 schematically illustrates an example photonic crystal structure comprising a first PCS and a second PCS substantially parallel to the first PCS.

[0019] Figure 9 is a plot of various normalized transmission spectra measured from a photonic crystal structure comprising a pair of PCSs.

[0020] Figures 10A-10C schematically illustrate the dependence of the resonance frequencies of a photonic crystal structure comprising a first PCS and a second PCS.

[0021] Figure 11 schematically illustrates the transmission spectra of two PCSs coupled in the near-field configuration when the PCSs are laterally displaced from one another.

[0022] Figure 12 illustrates the measured transmission spectra corresponding to TE polarized light incident on the PCS at various incidence angles.

[0023] Figures 13A-13D schematically illustrate example PCS structures having at least one photonic crystal defect.

[0024] Figures 14A and 14B schematically illustrate an example implementation for mirror-symmetry breaking in a PCS structure compatible with certain embodiments described herein.

[0025] Figure 15 schematically illustrates several example hole structures which break or remove one or more of the mirror symmetries of the PCS unit cell.

[0026] Figure 16A schematically illustrates a unit cell of a PCS having circularly symmetric holes on a periodic square lattice distribution.

[0027] Figures 16B-16E schematically illustrate the dot products of various resonance modes of the PCS with plane waves polarized in the horizontal direction (x-polarization) and with plane waves polarized in the vertical direction (y-polarization).

[0028] Figure 17A schematically illustrates an example unit cell of a PCS having holes on a periodic square lattice distribution, in which each hole comprises a small region to one side of the hole.

[0029] Figures 17B and 17C schematically illustrate an asymmetric resonance mode of the PCS of Figure 17A.

[0030] Figure 17D schematically illustrates the dot product of the odd-symmetric resonance mode with an incident plane wave with y-polarization.

[0031] Figure 18A schematically illustrates a PCS unit cell with the circularly symmetric hole of Figure 16A having four mirror symmetry axes.

[0032] Figure 18B schematically illustrates two doubly degenerate resonances and four non-degenerate resonances of the PCS structure of Figure 18A.

[0033] Figure 18C schematically illustrates x-polarized and y-polarized incident plane waves and the corresponding electric fields.

[0034] Figure 18D schematically illustrates a PCS unit cell with an asymmetric hole that is missing a mirror symmetry about the horizontal axis.

[0035] Figure 18E schematically illustrates a PCS unit cell with a rotationally-asymmetric hole.

[0036] Figures 19A and 19B show finite-difference time-domain simulations (FDTD) of transmission spectra for the three different hole shapes of Figures 18A, 18D, and 18E for polarizations perpendicular and parallel, respectively, to the hole elongations.

[0037] Figures 20A and 20B shows FDTD simulations of transmission spectra for incident light with polarizations perpendicular and parallel, respectively, to the hole elongations.

[0038] Figures 21A-21C are scanning-electron microscopy images of PCS structures with circularly-symmetric holes, mirror-asymmetric holes, and rotationally-asymmetric holes, respectively.

[0039] Figures 21D-21F are scanning-electron microscopy images of the circularly-symmetric holes, mirror-asymmetric holes, and rotationally-asymmetric holes, respectively.

[0040] Figures 22A and 22B show experimental measurements of the transmission spectrum for the three different PCS structures for polarizations perpendicular and parallel, respectively, to the hole elongations.

[0041] Figure 23 illustrates the transmission spectra for the perpendicular polarization case of Figure 22A on a larger wavelength range.

[0042] Figure 24 schematically illustrates an example acoustic sensor system having a housing compatible with certain embodiments described herein.

[0043] Figure 25 schematically illustrates an example acoustic sensor system having a secondary housing compatible with certain embodiments described herein.

[0044] Figure 26 schematically illustrates another example acoustic sensor system having a secondary housing compatible with certain embodiments described herein.

[0045] Figure 27 schematically illustrates an example acoustic sensor system having a metal layer on the optical fiber and a single PCS compatible with certain embodiments described herein.

[0046] Figure 28 schematically illustrates an example acoustic sensor system having a fiber Bragg grating and a single PCS compatible with certain embodiments described herein.

[0047] Figure 29 schematically illustrates a perspective view of an example configuration of an acoustic sensor system coupled to one end of an optical fiber.

[0048] Figures 30A-30Q schematically illustrate an example fabrication process flow compatible with certain embodiments described herein for the components of the acoustic sensor system.

[0049] Figure 31 schematically illustrates an example configuration of a movable reflective element (*e.g.*, a membrane) and an optical fiber.

[0050] Figure 32 is a graph of an optical resonance as a function of wavelength.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0051] Present-day optical resonators which have sufficient quality factors to achieve sensitivities comparable to those of piezoelectric transducers are typically large and impractical to fabricate, install, align, and operate. In contrast, certain embodiments described herein comprise an acoustic sensor based on optical resonators formed by photonic crystal slab (PCS) structures with apertures which are orders of magnitude smaller than those of traditional optical cavities. The small size of certain such embodiments provides a sensitivity comparable to that of piezoelectric and capacitive displacement sensors for frequencies larger than about 10 kHz. Photonic crystal structures comprising a pair of PCSs can be used to provide notch and bandpass transmission and reflection filters, and such structures can be utilized in acoustic sensor systems compatible with various applications (*e.g.*, oil exploration, undersea acoustic wave detection).

[0052] PCS structures have been used previously as filters and mirrors, in the same way as multi-layer dielectric stacks. However, PCS structures have several advantages over multi-layer mirrors, including but not limited to, being a single dielectric layer, being compatible with microelectromechanical systems (MEMS), and having unique properties that

are difficult or impossible to achieve with multilayer stacks and that can be controlled through geometrical parameters. For example, PCS structures can have a high reflectivity over a broad range of wavelengths (*e.g.*, an observed extinction in transmission of over 99% in a range of wavelengths greater than about 30 nanometers), and can be used as efficient filters at telecom wavelengths (*e.g.*, 1540 nanometers) with sharp resonances observed to have Q of about 5000. In addition, a PCS structure can be used as a circular polarization beam-splitter separating plane-polarized light into its spin-polarized components. Also, though an introduction of a small form birefringence, a PCS structure can act as a dual quarter-wave retarder-based polarizing beam splitter, which separates an incoming wave equally into two orthogonal polarizations through reflection and transmission.

[0053] Figure 1 schematically illustrates an example acoustic sensor 10 compatible with certain embodiments described herein. The acoustic sensor 10 comprises at least one photonic crystal structure 20 having at least one optical resonance with a resonance frequency and a resonance lineshape. The acoustic sensor 10 further comprises a housing 30 substantially surrounding the at least one photonic crystal structure 20 and mechanically coupled to the at least one photonic crystal structure 20. At least one of the resonance frequency and the resonance lineshape of the at least one photonic crystal structure 20 is responsive to acoustic waves 40 incident upon the housing 30. As illustrated by Figure 1, in certain embodiments, the acoustic sensor 10 further comprises an optical fiber 50 optically coupled to the at least one photonic crystal structure 20.

Single PCS structures

[0054] In certain embodiments, the at least one photonic crystal structure 20 comprises a PCS 70, an example of which is schematically illustrated by Figure 2A. The PCS 70 comprises a first material 72 and an array of regions 74 within the PCS 70. The regions 74 comprise a second material 76 having a refractive index different from a refractive index of the first material 72. The PCS 70 of Figure 2A has a thickness T and a substantially planar configuration.

[0055] In certain embodiments, the first material 72 comprises a solid dielectric material, examples of which include but are not limited to, silicon, silica, silicon nitride, ceramics, and plastics. In certain embodiments, the first material 72 comprises a solid

semiconductor material, examples of which include but are not limited to, silicon, germanium, indium phosphide, gallium arsenide, or other III-V semiconductor materials. In certain embodiments, the second material 76 comprises a gas (*e.g.*, air). In certain embodiments, the second material 76 comprises a fluid, examples of which include but are not limited to, water, isopropanol, ethanol, methanol, and other alcohols.

[0056] In certain embodiments, the thickness T of the PCS 70 is in a range between about 100 nanometers and about 1000 nanometers. In certain embodiments, the PCS 70 has a substantially square shape, while in other embodiments, the PCS 70 has a substantially circular, rectangular, hexagonal, elliptical, or other shape.

[0057] In certain embodiments, the regions 74 have a maximum width along a direction substantially parallel to the PCS 70 in a range between about 100 nanometers and about 1500 nanometers. In certain embodiments, the regions 74 have a substantially circular shape, while in certain other embodiments, the regions 74 have a substantially elliptical, oval, square, rectangular, triangular, pentagonal, hexagonal, semicircular, or other shape.

[0058] In certain embodiments, the array of regions 74 has a substantially two-dimensionally-periodic distribution. The periodicities of the distribution in two different directions generally parallel to the PCS 70 are substantially the same in certain embodiments, while in certain other embodiments, the periodicities are different. In certain embodiments, the center-to-center distance between nearest-neighboring regions 74 is in a range between about 100 nanometers and about 1550 nanometers. In certain embodiments, the substantially two-dimensionally-periodic distribution of the array of regions 74 is square, while in certain other embodiments, the substantially two-dimensionally-periodic distribution is rectangular, triangular, square, rhombic, oblique, or hexagonal. Other substantially two-dimensionally-periodic distributions are also compatible with certain embodiments described herein.

[0059] In certain embodiments, the regions 74 comprise a plurality of holes extending at least partially through the thickness of the PCS 70, containing the second material 76, and having a substantially two-dimensionally-periodic distribution within the PCS 70. For example, Figure 2A schematically illustrates an example PCS 70 having an array of regions 74 comprising substantially circular holes extending completely through the thickness of the PCS 70 and having a substantially square distribution, in accordance with

certain embodiments described herein. Figure 2B illustrates a scanning electron microscope micrograph of portions of such an example PCS 70. Figure 2C schematically illustrates another example PCS 70 having a substantially square array of regions 74 comprising substantially circular holes extending only partly through the thickness T of the PCS 70, thereby having a depth D less than the thickness T of the PCS 70, in accordance with certain other embodiments described herein.

[0060] Figure 2D schematically illustrates another example PCS 70 having a substantially square distribution of protrusions 78 (*e.g.*, pillars) having a substantially circular cross-section in a plane substantially parallel to the PCS 70, in accordance with certain other embodiments described herein. The protrusions 78 have a height H above the PCS 70 in a range between about 100 nanometers and about 1000 nanometers. In certain embodiments, the height H is greater than the thickness T, while in certain other embodiments, the height H is less than or equal to the thickness T. In certain embodiments, the protrusions 78 comprise the same material as does the underlying portions of the PCS 70, while in certain other embodiments, the protrusions 78 comprise a different material (*e.g.*, the PCS 70 comprises silicon oxide while the protrusions 78 comprise silicon). In certain embodiments, the PCS 70 comprises a dielectric material (*e.g.*, silicon, silica, silicon nitride, ceramics, plastics) or a semiconductor material (*e.g.*, silicon, germanium, indium phosphide, gallium arsenide, or other III-V semiconductor). In certain embodiments, the protrusions 78 comprises a dielectric material (*e.g.*, silicon, silica, silicon nitride, ceramics, plastics) or a semiconductor material (*e.g.*, silicon, germanium, indium phosphide, gallium arsenide, or other III-V semiconductor). Other shapes, sizes, and distributions of the protrusions 78 are also compatible with certain embodiments described herein.

[0061] Figures 2E and 2F schematically illustrate cross-sectional views of other example slabs 70 having a plurality of elongated regions 74 with a substantially one-dimensionally-periodic distribution (*e.g.*, a one-dimensional grating). In Figures 2E and 2F, the regions 74 extend in a direction substantially perpendicular to the cross-sectional view. In certain embodiments, the spacing between adjacent regions 74 is in a range between about 100 nanometers and about 1550 nanometers. In certain embodiments, the widths of the regions 74 are in a range between about 100 nanometers and about 1500 nanometers. In

certain embodiments, the center-to-center spacing between adjacent regions 74 is in a range between about 100 nanometers and about 1550 nanometers.

[0062] As schematically illustrated by Figure 2E, in certain embodiments, the PCS 70 comprises a first material (*e.g.*, a dielectric material such as silica, silicon oxide, or silicon nitride) with regions 74 comprising troughs or grooves 80 within the PCS 70 containing the second material 76 (*e.g.*, air or water). In certain embodiments, the grooves 80 extend completely through the thickness *T* of the PCS 70, while in certain other embodiments, the grooves 80 extend only partly through the thickness *T* of the PCS 70. The depth *D* of the grooves 80 is in a range between about 10 nanometers and about 1000 nanometers. In certain embodiments, the grooves 80 have a generally square, trapezoidal, curved or “U”-shaped, or triangular cross-section in a plane substantially perpendicular to the PCS 70. Other shapes and sizes of the grooves 80 are also compatible with certain embodiments described herein.

[0063] In certain other embodiments, as schematically illustrated by Figure 2F, the regions 74 comprise protrusions 82 having a height *H* above the PCS 70 in a range between about 10 nanometers and about 1000 nanometers. The protrusions 82 of certain embodiments comprise the same material as does the underlying portions of the PCS 70, while in certain other embodiments, the protrusions 82 comprises a different material from the first material 72 (*e.g.*, the PCS 70 comprises silicon oxide while the protrusions 82 comprise silicon). In certain embodiments, the PCS 70 comprises a dielectric material (*e.g.*, silicon, silica, silicon nitride, ceramics, plastics) or a semiconductor material (*e.g.*, silicon, germanium, indium phosphide, gallium arsenide, or other III-V semiconductor). In certain embodiments, the protrusions 82 comprises a dielectric material (*e.g.*, silicon, silica, silicon nitride, ceramics, plastics) or a semiconductor material (*e.g.*, silicon, germanium, indium phosphide, gallium arsenide, or other III-V semiconductor). In certain embodiments, the protrusions 82 have a generally square, trapezoidal, curved or “U”-shaped, or triangular cross-section in a plane substantially perpendicular to the PCS 70. Other shapes and sizes of the protrusions 82 are also compatible with certain embodiments described herein.

[0064] In certain embodiments, the at least one photonic crystal structure 20 comprises a single PCS 70 that exhibits at least one optical resonance having a resonance

frequency and a resonance lineshape. Figures 3A-3C schematically illustrates an example PCS 70 (shown on the left) exhibiting an optical resonance in the simulated transmitted optical power spectrum (shown on the right) for light incident in a direction substantially perpendicular to the PCS 70. In Figures 3A-3C, the optical resonance is shown as a dip in the transmitted optical power spectrum. The horizontal axes of the simulated transmitted optical power spectra of Figures 3A-3C are in units of (c/a) , where c is the speed of light in vacuum and a is the lattice constant of the PCS 70 (*e.g.*, the center-to-center spacing of the holes). Figure 3A illustrates the PCS 70 with no forces applied, Figure 3B illustrates the PCS 70 with a compressive force applied, and Figure 3C illustrates the PCS 70 with an expansive or stretching force applied. The compressive force shifts the frequency of the optical resonance towards higher frequencies, as shown by a comparison of Figures 3A and 3B. The expansive force shifts the frequency of the optical resonance towards lower frequencies, as shown by a comparison of Figures 3A and 3C.

[0065] Figure 4 schematically illustrates the measured resonance wavelength shift for substantially perpendicularly incident light on an example PCS 70 as a function of temperature. For temperature T_0 of about 25° C, the resonance wavelength is about 1431 nanometers, for temperature T_1 of about 450° C, the resonance wavelength is about 1434 nanometers, and for temperature T_2 of about 800° C, the resonance wavelength is about 1436 nanometers. By changing the temperature of the PCS 70, both the geometry is changed via thermal expansion and the dielectric constant is changed, both of which contribute to the shift of the resonance wavelength.

[0066] Figure 5 illustrates the resonance wavelength shift for substantially perpendicularly incident light on an example PCS 70 as a function of mechanical forces applied to the PCS 70. For the measurements illustrated by Figure 5, one end of an example PCS 70 was fixedly mounted to a stationary position and the other end of the PCS 70 was mounted to a piezoelectric oscillator which was oscillated at 4.7 kHz using a 4-volt peak-to-peak voltage. The relative sensitivity of the change in optical power with respect to different optical wavelengths for a constant acoustic power generally follows the slope of the optical transmission spectrum of the PCS 70.

[0067] Similar behavior was observed for a PCS 70 in the experimental apparatus schematically illustrated by Figure 6. As shown by Figure 6, one end of a 1-centimeter long PCS 70 was fixedly mounted (*e.g.*, by epoxy) to a stationary position, and the other end 84 was fixedly mounted (*e.g.*, by epoxy) to one end of a movable cantilever which was used to reduce the frequency of the PCS structure. An audio speaker 86 facing the cantilever and spaced about 3 centimeters from the cantilever was oscillated at about 500 Hz using a 10-volt peak-to-peak voltage.

[0068] Figures 7A and 7B schematically illustrate an example acoustic sensor 10 having photonic crystal structure 20 comprising a single PCS 70 in accordance with certain embodiments described herein. The PCS 70 is mounted with a first end 92 fixedly mounted to a stationary position and a second end 94 fixedly mounted to a movable membrane 96. In certain embodiments, the membrane 96 is a portion of the housing 30. An optical fiber 50 is positioned to irradiate the PCS 70 with light in a direction substantially perpendicular to the PCS 70. In certain embodiments, light reflected by the PCS 70 re-enters the optical fiber 50 and is detected by an optical sensor (not shown), while in certain other embodiments, light transmitted through the PCS 70 is detected by an optical sensor (not shown). In certain embodiments, acoustic waves 40 incident on the membrane 96 induce forces (*e.g.*, strain) in the plane of the PCS 70 (*e.g.*, by stretching and compressing the PCS 70), thereby shifting at least one of the resonance frequency and the resonance lineshape of the PCS 70, as detected by either the reflection spectrum, the transmission spectrum, or both. In certain other embodiments, the PCS 70 is mounted to the membrane 96 such that acoustic waves 40 incident on the membrane 96 induce strain in the PCS 70 by bending the PCS 70. In certain such embodiments, the measured Q for the resonance is about 2500 to 3000. In certain such embodiments, the corresponding sensitivity of the acoustic sensor 10 is about 1 micropascal/Hz^{1/2}, and the dynamic range is limited by the yield strength of the PCS 70 to be about 50 decibels. In an example embodiment, a theoretical strain of about 1×10^{-5} applied to a PCS 70 yields a 10^{-3} change in the transmitted power at a wavelength of about 1550 nanometers.

Dual PCS structures

[0069] In certain embodiments, the photonic crystal structure 20 comprises a first PCS 100 and a second PCS 102 substantially parallel to the first PCS 100, as schematically illustrated by Figure 8. Each of these PCSs 100, 102 can have physical parameters (*e.g.*, thicknesses, region sizes, materials, periodicities, distributions) as described above for the single PCS structure.

[0070] In certain embodiments, there is no physical contact between the first PCS 100 and the second PCS 102. The first and second PCSs 100, 102 can undergo displacements relative to one another in response to incident acoustic waves 40. In certain embodiments, light is incident on the first and second PCSs 100, 102 in a direction substantially perpendicular to the PCSs 100, 102. In certain embodiments, the light is provided by an optical fiber 50, as schematically illustrated by Figure 8, while in certain other embodiments, the light is collimated prior to irradiating the PCSs 100, 102.

[0071] Figure 9 is a plot of various normalized transmission spectra measured from a photonic crystal structure 20 comprising a pair of PCSs (*e.g.*, as shown in Figure 8), each transmission spectrum corresponding to a different manual displacement between the two PCSs. The measured transmission spectra of Figure 9 were obtained by using two PCSs in proximity to one another and a micron-actuator to manually vary the displacement between the two slabs. As can be seen from Figure 9, the pair of PCSs exhibits optical resonances each having a resonance frequency and a resonance lineshape, and that both the resonance frequency and the resonance lineshape are responsive to changes of the relative position between the two PCSs. As shown in Figure 9, one example resonance of the pair of PCSs has a tuning bandwidth of about 50 nanometers at a center wavelength of about 1377 nanometers. This resonance is sufficiently sharp (*e.g.*, about 0.5 THz with a peak-to-floor ratio of 25 dB) to be used in an acoustic sensor system. Theoretical calculations can be used to design PCS structures with sharper resonances, to be used in acoustic sensor systems with even higher sensitivities.

[0072] The resonance frequency and the resonance lineshape of the pair of PCSs are both dependent on changes of the perpendicular distance between the two PCSs and on changes of the lateral relative positions of the two PCSs. The two PCSs exhibit optical

behavior similar to that of a single PCS, and through the relative displacements, the geometry and optical properties of the photonic crystal structure can be tuned. U.S. Patent Application Publication No. US 2004/0080726 A1, discloses calculations (*e.g.*, temporal coupled-mode theory calculations and finite-difference time-domain simulations) of the transmission spectrum for a pair of PCSs as functions of the frequency of the incident light and of the displacement between the two PCSs. These calculations replicate the behavior shown in Figure 9.

[0073] In certain embodiments, the two PCSs are brought sufficiently close to one another that they are optically coupled in the near-field to one another (referred to herein as a near-field configuration). In certain embodiments, the two PCSs are spaced apart from one another such that the PCSs are not optically coupled to one another, but form a cavity (referred to herein as a Fabry-Perot configuration). In either the Fabry-Perot configuration or the near-field configuration, the optical resonances shift in frequency (or wavelength) with changing displacement between the two PCSs. Thus, the amount of displacement between the two PCSs can be detected by measuring the transmitted power (or the reflected power) at a predetermined frequency (or wavelength). In general, the near-field configuration generates a larger shift of frequency (or wavelength) than does the Fabry-Perot configuration, such that the near-field configuration has a higher sensitivity to displacements than does the Fabry-Perot configuration.

[0074] In certain embodiments in which the two PCSs are optically coupled together in the near-field configuration, the optical resonances are split into two resonances. The amount of splitting varies with the displacement between the two PCSs which, in certain embodiments, provides a measure of the displacement. Figures 10A-10C schematically illustrate the dependence of the resonance frequencies of the photonic crystal structure 20 comprising a first PCS 100 and a second PCS 102. In Figure 10A, a single PCS 70 is schematically shown with its transmission spectrum having a single optical resonance mode. In Figure 10B, a pair of PCSs 100, 102 coupled in the near-field configuration are schematically shown and the transmission spectrum has a pair of optical resonance modes having frequencies that are split from one another. In Figure 10C, one or both of the PCSs are displaced in a direction substantially perpendicular to the PCSs such that the distance

between the two PCSs 100, 102 is decreased, thereby shifting the frequencies of the two modes such that the splitting between the frequencies of the two modes increases.

[0075] In certain embodiments in which the two PCSs are coupled in the near-field configuration, additional resonances appear in the transmission spectra when the PCSs are laterally displaced relative to one other in a direction substantially parallel to the PCSs, as schematically illustrated by Figure 11. As discussed more fully below, these resonances are generated by breaking the mirror symmetry of the double PCS structure, which allows incident light to couple to non-degenerate resonances. These additional resonances shift in frequency (or wavelength) as a function of the perpendicular displacement between the two PCSs. These additional resonances shift in frequency (or wavelength) and their lineshapes (e.g., linewidths) also change as a function of the lateral displacement parallel to the two PCSs. In certain embodiments, by optically coupling the two PCSs, the linewidth and the frequency of these additional resonances can advantageously be tuned dynamically by displacements between the two PCSs perpendicular to the PCSs and parallel to the PCSs. In certain embodiments, a sub-Ångstrom displacement (either perpendicular or parallel to the PCSs) between the two PCSs introduces a detectable change in the transmitted or reflected power at a sensitive resonance wavelength. In certain embodiments, electrical actuation can be used to shift the PCSs in a direction generally parallel to the PCSs and using resonance frequency shifts due to acoustic-wave-induced displacements between the PCSs in a direction generally perpendicular to the PCSs. Certain such embodiments are advantageously used in acoustic sensor systems.

Fiber Compatibility

[0076] The sharp resonances of typical optical resonators or filters are sensitive to the incident angle of the light. Typically, to avoid this sensitivity to the incident angle, the incident light is collimated so as to approximate a plane wave. When using an optical fiber as the light source, the light emitted by the optical fiber possesses a certain angular distribution which is typically collimated for present-day optical resonators using additional collimation optics and additional fiber-to-fiber coupling hardware.

[0077] In contrast, certain embodiments described herein have one or more resonances which are substantially independent of the incidence angle of the optical beam

over a range of incidence angles. In certain such embodiments, the light emitted by the optical fiber has an angular distribution such that a substantial fraction (*e.g.*, more than 50%) of the light incident on the PCS is within the range of incidence angles for which the resonance frequency of such resonances does not change. For such resonances, the linewidth of the resonance is also essentially independent of the incidence angle. Such an angular insensitivity implies that the resonances do not have to be excited by a collimated beam (*e.g.*, by light which approximates a plane wave).

[0078] In certain embodiments in which the resonance is insensitive to the incidence angle, the various angular components of the light emitted by the optical fiber are all affected by the PCS structure in the same way, so the acoustic sensor behaves in much the same way as if the light was collimated. In certain such embodiments, since the resonance is insensitive to the incidence angle, the light from the optical fiber directly impinges the PCS structure without intervening collimation optics between the optical fiber and the PCS structure. Certain such embodiments advantageously avoid using complicated collimation or coupling components, thereby simplifying integration and packaging and lowering cost.

[0079] The fiber-compatibility of the PCS structure advantageously permits certain embodiments described herein to be easily incorporated into already-present and widely-used fiber-based acoustic sensor systems. In addition, the angular insensitivity of the PCS structure advantageously facilitates incorporating several types of filters into fiber-based optical communication networks.

[0080] In an example embodiment, a silicon-nitride PCS illuminated by transverse-electric (TE) polarized light has a resonance mode with a wavelength of about 695 nanometers. Figure 12 illustrates the measured transmission spectra corresponding to TE polarized light incident on the PCS at various incidence angles. As shown in Figure 12, the transmission spectra have various features which are dependent on the incidence angle, but the resonance mode at about 695 nanometers is substantially insensitive to the incidence angle of the TE polarized light. In another example embodiment, the silicon-nitride PCS is illuminated by transverse-magnetic (TM) polarized light, and exhibits a resonance mode with a wavelength of about 770 nanometers, and this resonance is substantially insensitive to the incidence angle of the TM polarized light.

[0081] In certain embodiments in which the acoustic sensor 10 further comprises an optical fiber 50 optically coupled to the at least one photonic crystal structure 20 (e.g., as schematically illustrated by Figure 1), the light emitted from the optical fiber 50 is incident to the at least one photonic crystal structure 20 in a range of incidence angles within about 10 degrees from a direction perpendicular to the at least one photonic crystal structure 20. In certain such embodiments, the light is not collimated between being emitted from the optical fiber 50 and reaching the at least one photonic crystal structure 20.

Tailoring the Optical Resonance

[0082] Certain eigenmodes in a PCS possess infinite lifetimes, hence are uncoupled to outside radiation at normal incidence. Therefore, in present-day optical resonator systems utilizing photonic crystals, it is generally not possible to couple to certain resonances (referred to herein as non-degenerate resonances) with normally-incident plane waves due to a symmetry mismatch between the resonance mode and the incident wave. This effect was observed experimentally by Pacradouni *et al.*, “*Photonic band structure of dielectric membranes periodically textured in two dimensions*,” Phys. Rev. B, vol. 62, page 4204 (2000), and discussed theoretically by Paddon and Young, “*Two-dimensional vector-coupled-mode theory for textured planar waveguides*,” Phys. Rev. B, vol. 61, page 2090 (2000). Using group theoretical arguments, Ochiai and Sakoda, in “*Dispersion relation and optical transmittance of a hexagonal photonic crystal slab*,” Phys. Rev. B, vol. 63, page 125107 (2001), showed that these resonances are uncoupled due to a symmetry mismatch with outside radiation.

[0083] However, measurements and group theory calculations show that it is possible to couple to these non-degenerate resonances in a PCS lacking mirror symmetry. As described more fully below, simulations and experimental results show that such non-degenerate resonances can indeed be excited by breaking the mirror symmetry of the PCS structure, either by breaking the periodicity of the lattice array or by breaking the mirror symmetry of the unit cells (e.g., in a square lattice array). In addition, it is possible to control the sharpness (e.g., linewidth, quality factor) of such resonances by adjusting the degree of asymmetry (e.g., the size of the non-symmetric region of the holes of the PCS structure). In certain embodiments, the quality factor of these resonances can be tuned from a finite

minimum to infinity. Resonances sharper than the spectral linewidth of the source are generally practically useless, so in certain embodiments, the tuning is done from a finite minimum to a finite maximum (as determined by the linewidth of the incident light).

[0084] Such PCS structures are expected to have applications for mode selection and linewidth control in lasers, and will find use in acoustic sensor applications by advantageously improving and controlling the sensitivity of the acoustic sensor system. Certain embodiments described herein advantageously improve the sensitivity of the acoustic sensor system up to a limit imposed by other factors, such that the PCS structure is not the limiting element. In certain embodiments in which a lower sensitivity is desirable (*e.g.*, to improve the dynamic range), the sensitivity of the acoustic sensor system is lowered such that the PCS structure is the limiting element. In certain embodiments, the lack of mirror symmetry is implemented for a PCS structure with a triangular lattice array or any other lattice array geometry, or in general, for any kind of an optical resonator system.

[0085] In certain embodiments, the non-degenerate resonances of a PCS with a symmetric structure that are uncoupled to normally-incident plane waves are excited in a mirror-symmetry-lacking PCS structure. In certain embodiments, one or more of the mirror symmetries of the PCS structure is advantageously broken or removed to allow coupling to the non-degenerate resonances. In certain embodiments, the coupling to these non-degenerate resonances is advantageously controlled by selecting the degree of asymmetry. In certain embodiments, the at least one photonic crystal structure has a symmetry axis and the light incident normal to the at least one photonic crystal structure is polarized in a direction substantially perpendicular to the symmetry axis. In certain other embodiments, the normally-incident light is polarized in a direction substantially parallel to the symmetry axis.

[0086] In certain embodiments, the asymmetry of the PCS structure is generated by an asymmetry in the substantially periodic distribution of holes. Figures 13A-13D schematically illustrate example PCS structures having at least one photonic crystal defect in the substantially periodic distribution. The PCS structure of Figure 13A has a photonic crystal defect comprising a missing hole, and such a photonic crystal defect possesses mirror symmetry with respect to the horizontal and vertical axes. In certain embodiments, the PCS structure comprises at least one hole with a reduced size or an increased size as compared to

the other holes of the PCS structure. In certain embodiments, this reduced-size or increased-size hole is at an expected lattice position of the substantially periodic distribution, while in other embodiments, it is displaced from the expected lattice position. In certain other embodiments, this reduced-size or increased-size hole is in proximity to the position of a missing hole. For example, Figure 13B schematically illustrates a PCS structure with a hole having a reduced size and adjacent to the missing hole position. Figure 13C shows a hole adjacent to the missing hole position to be slightly shifted from its expected lattice position of the substantially periodic distribution. Figure 13D shows a hole which itself lacks a mirror symmetry acting as the defect. In certain other embodiments, the dielectric constant of a portion of the PCS structure is reduced or increased to break the mirror symmetry. For example, at least one of the holes of the PCS structure can contain a third material having a refractive index different from the refractive indices of the first material or the second material. The photonic crystal defects of Figures 13B, 13C, and 13D lack mirror symmetry with respect to the horizontal axis. Various possibilities to break the mirror symmetry, not limited to those schematically illustrated by Figures 13A-13D, are compatible with embodiments described herein. While Figures 13A-13D have been described in terms of a PCS structure comprising a plurality of holes, persons skilled in the art recognize that a PCS structure comprising a plurality of protrusions would exhibit similar behavior.

[0087] Figures 14A and 14B schematically illustrate an example implementation for mirror-symmetry breaking in a PCS structure compatible with certain embodiments described herein. The PCS structure shown in Figure 14A possesses mirror symmetry with respect to both the horizontal and vertical axes. The PCS structure shown in Figure 14B lacks mirror symmetry with respect to the horizontal axis.

[0088] Figure 15 schematically illustrates several example hole structures which break or remove one or more of the mirror symmetries of the PCS unit cell. Each of the structures schematically illustrated by Figure 15 lack mirror symmetry with respect to the horizontal axis, while possessing mirror symmetry with respect to the vertical axis. Besides the structures schematically illustrated by Figure 15, there is an infinite number of hole shapes compatible with embodiments described herein.

[0089] Figure 16A schematically illustrates a unit cell 150 of a PCS having circularly symmetric holes 152 on a periodic square lattice distribution. The dashed lines of Figure 16A denote various mirror symmetry axes 154 of the PCS. Figures 16B-16E schematically illustrate the dot products of various resonance modes of the PCS with plane waves polarized in the horizontal direction (x-polarization) and with plane waves polarized in the vertical direction (y-polarization). The dot products schematically illustrated by Figures 16B and 16C are not equal to zero, so these two resonance modes couple to incident plane wave. However, the dot products schematically illustrated by Figures 16D and 16E equal zero, so this resonance mode does not couple to incident plane waves, and is a non-degenerate resonance.

[0090] In certain embodiments, one or more of the mirror symmetries of the PCS structure is broken or removed. In certain such embodiments, one or more of the mirror symmetries of the unit cell of the periodic array of holes in the PCS is removed. Figure 17A schematically illustrates an example unit cell 160 of a PCS having holes 162 on a periodic square lattice distribution, in which each hole 162 comprises a small region 163 to one side of the hole 162. The region 163 of Figure 17A has a generally square shape, while in certain other embodiments, the region 163 has another shape (*e.g.*, triangular, rectangular, irregular). As shown in Figure 17A, the hole 162 does not have a mirror symmetry about the horizontal axis 164, as denoted by the horizontal dashed line marked by an "X," but the hole 162 maintains the mirror symmetry about the vertical axis 165. The region 163 removes one of the mirror symmetries of the unit cell 160, as compared to the circularly symmetric hole 150 of Figure 16A, thereby changing the symmetry of the non-degenerate resonances. As schematically illustrated by Figures 17B and 17C, the region 163 modifies the resonance mode schematically illustrated by Figures 16D and 16E to be an asymmetric resonance mode, which can be equated to the sum of an even-symmetric resonance mode and an odd-symmetric resonance mode. As schematically illustrated by Figure 17D, the dot product of this odd-symmetric resonance mode with an incident plane wave with y-polarization is non-zero, indicating that this odd-symmetric resonance mode can couple to incident plane waves. Thus, the change of the symmetry of the resonance modes by the asymmetric hole 162 makes coupling to the non-degenerate resonances possible using normally-incident plane waves.

[0091] Figure 18A schematically illustrates a PCS unit cell 150 with the circularly symmetric hole 152 of Figure 16A having four mirror symmetry axes 154. Figure 18B schematically illustrates two doubly degenerate resonances ($E^{(1)}$ and $E^{(2)}$) and four non-degenerate resonances (A_1 , A_2 , B_1 , B_2) of the PCS structure, and Figure 18C schematically illustrates x-polarized (e_x) and y-polarized (e_y) incident plane waves and the corresponding electric fields. The hole 152 of Figure 18A has a substantially symmetric shape possessing mirror symmetry with respect to a first axis (*e.g.*, $\hat{\sigma}_x$) along the PCS 70 and with respect to a second axis (*e.g.*, $\hat{\sigma}_y$) along the PCS 70, the second axis substantially perpendicular to the first axis. The dot products $E^{(1)} \cdot e_y$ and $E^{(2)} \cdot e_x$ are non-zero, indicating that these doubly degenerate resonances of Figure 18B couple to y-polarized and x-polarized incident plane waves, respectively. The dot products $A_1 e_x$, $A_2 e_x$, $B_1 e_x$, $B_2 e_x$, $A_1 e_y$, $A_2 e_y$, $B_1 e_y$, and $B_2 e_y$ are each equal to zero, indicating that these non-degenerate resonances of Figure 18B are not coupled to either x-polarized or y-polarized incident plane waves.

[0092] In certain embodiments, the coupling to the non-degenerate resonances can be controlled by advantageously selecting the degree of asymmetry of the hole. Figure 18D schematically illustrates a PCS unit cell 160 with the asymmetric hole 162 with a region 163 to one side. The asymmetric hole 162 has a substantially asymmetric shape lacking mirror symmetry with respect to one axis along the PCS 70. For example, as shown in Figure 18D, the hole 162 has the mirror symmetry about the horizontal axis broken and has the rotational symmetry broken, possesses mirror symmetry with respect to the vertical axis 165 along the PCS 70, the vertical axis 165 substantially perpendicular to the horizontal axis. Figure 18E schematically illustrates a PCS unit cell 170 with a hole 172 having two similar regions 173 positioned to maintain the two mirror symmetry axes 174, while the rotational symmetry remains broken. The PCS structure corresponding to Figure 18E can be used to demonstrate that it is the breaking of the mirror symmetry that is responsible for the excitation of the sharp non-degenerate resonances. As described more fully below, for PCS structures where only the rotational symmetry is broken (*e.g.*, for elliptical holes), the non-degenerate resonances remain uncoupled to the normally-incident plane waves.

[0093] Figures 19A and 19B show finite-difference time-domain simulations (FDTD) of transmission spectra for these three different hole shapes for polarizations

perpendicular and parallel, respectively, to the hole elongations. The transmission spectra of Figures 19A and 19B correspond to normal incidence transmission through a PCS structure with circular holes, mirror-asymmetric holes, and rotationally-asymmetric holes.

[0094] The simulations were done for a dielectric constant of 12, corresponding roughly to the dielectric constant of Si or GaAs at optical frequencies. The PCS thickness was chosen to be $0.75a$, where a is the lattice constant of the periodic structure. The radius of the circular portion of the hole was chosen to be $0.4a$ and the width of the square-shaped regions was chosen to be $0.025a$. As can be seen in Figures 19A and 19B, additional sharp features (denoted by arrows) due to non-degenerate resonances are present only in the PCS structure lacking mirror symmetry. Each of these additional resonances appears only for one polarization and not for the other, thereby demonstrating the non-degenerate nature of these resonances.

[0095] In certain embodiments, the magnitude of the asymmetry of the holes is selected to provide a desired amount of coupling to normally-incident plane waves. Figures 20A and 20B shows FDTD simulations of transmission spectra for incident light with polarizations perpendicular and parallel, respectively, to the hole elongations. To show that the quality factor of these resonances can be controlled, the size of the elongations was increased by 100% to $0.05a$. As shown by a comparison of Figures 20A and 20B with Figures 19A and 19B, the strength and linewidths of the non-degenerate resonances have increased with the increase in asymmetry. This behavior has also been measured from PCS structures with increasing asymmetry.

[0096] To demonstrate that the results of the analysis and simulations can be observed in a real structure, the three PCS structures generally corresponding to Figures 18A, 18D, and 18E were fabricated on free-standing silicon membranes. Figures 21A-21C are scanning-electron microscopy images of PCS structures with circularly-symmetric holes, mirror-asymmetric holes, and rotationally-asymmetric holes, respectively. Figures 21D-21F are scanning-electron microscopy images of the circularly-symmetric holes, mirror-asymmetric holes, and rotationally-asymmetric holes, respectively. The circular line overlayed on these SEM images facilitates seeing the small hole elongations of these PCS structures that produce the asymmetries. The material of the PCS was silicon, the thickness

of the PCS was about 450 nanometers, the period of the lattice array was about 1000 nanometers, and the diameter of the holes was about 450 nanometers.

[0097] Figures 22A and 22B show experimental measurements of the transmission spectrum for the three different PCS structures for polarizations perpendicular and parallel, respectively, to the hole elongations. Sharp doubly-degenerate modes are observed for both polarizations, as denoted with arrows (labeled as DD) in all three of the PCS structures. There are also broader doubly-degenerate resonances present which are not denoted by arrows. As shown in Figure 22A, there is an additional, relatively sharp resonance for the mirror-asymmetric PCS structure (corresponding to Figure 21B and Figure 21E) and this resonance is only present for one polarization (perpendicular to the hole elongation), showing its non-degeneracy (labeled as ND). There is a small difference in the transmission spectra for the two polarizations even for the case of the symmetric PCS structure (corresponding to Figure 21A and Figure 21D). This small difference is due to a small elongation of the lattice array in one direction due to the electron-beam exposure and subsequent fabrication steps used to form the PCS structure. However, this situation is not essential for the observation of the non-degenerate resonances.

[0098] The measured sharp resonances shown in Figures 22A and 22B do not vary over as large a transmission range as do the idealized calculations (which vary between 0 and 100% transmission in a range of one linewidth) due to the deterioration of the resonances through fabrication-related disorders. The measurements described herein were for a relatively large lattice array of size 100 microns by 100 microns, where disorder effects can play a significant role for sharp resonances. The angular content of the incident light with finite spot-size is another effect that can deteriorate sharp resonances. For a single defect cavity, such as one for a laser, the non-degenerate resonances can be much more dominant (*e.g.*, they can vary from 0 to 100%).

[0099] To illustrate that the non-degenerate resonance appears only in the mirror-asymmetric PCS structure (corresponding to Figure 21B and Figure 21E), Figure 23 illustrates the transmission spectra for the perpendicular polarization case of Figure 22A on a larger wavelength range. The non-degenerate nature of these resonances, combined with the fact that their inherently high quality factor can be tuned through a simple geometrical

parameter that can be controlled lithographically enable a variety of applications including acoustic sensing systems and devices for mode selection and linewidth control in lasers. Such structures will also find use as very sharp filters in sensor applications.

Acoustic sensor systems

[0100] Figure 24 schematically illustrates an example acoustic sensor system 200 compatible with certain embodiments described herein. In certain embodiments, the acoustic sensor system 200 comprises at least one photonic crystal structure 20 having at least one optical resonance with a resonance frequency and a resonance lineshape. The acoustic sensor system 200 further comprises a housing 30 substantially surrounding the at least one photonic crystal structure 20 and mechanically coupled to the at least one photonic crystal structure 20. At least one of the resonance frequency and the resonance lineshape of the at least one photonic crystal structure 20 is responsive to acoustic waves 40 incident upon the housing 30. As illustrated by Figure 24, in certain embodiments, the acoustic sensor system 200 further comprises an optical fiber 50 optically coupled to the at least one photonic crystal structure 20.

[0101] In certain embodiments, the acoustic sensor system 200 is compatible with operation in a liquid (*e.g.*, seawater) or other media. As schematically illustrated in Figure 24, an acoustic wave 40 impinges on, and is detected by, the acoustic sensor system 200.

[0102] In the embodiment schematically illustrated by Figure 24, the at least one photonic crystal structure 20 comprises two PCSs 70a, 70b optically coupled to one another and in close proximity to one another (referred to herein as a double-PCS structure). In certain embodiments the two PCSs 70a, 70b are substantially parallel to one another. In certain embodiments, the two PCSs 70a, 70b are optically coupled to each other in the near-field configuration. In certain other embodiments, the two PCSs 70a, 70b are placed further apart so that they are not optically coupled in the near-field configuration, but form a simple Fabry-Perot cavity (*i.e.*, the Fabry-Perot configuration). In certain embodiments, the resonances of the photonic crystal structure 20 shift in frequency (and in the corresponding wavelength) when the vertical distance between the two PCSs 70a, 70b is changed. Example photonic crystal structures 20 compatible with certain embodiments described herein are described in “*Displacement-sensitive photonic crystal structures based on guided resonance*

in photonic crystal slabs,” W. Suh *et al.*, Appl. Phys. Lett. vol. 82, No. 13, pages 1999-2001 (1999), and U.S. Patent Publication No. 2004/0080726.

[0103] In certain embodiments, the PCSs 70a, 70b undergo movement relative to one another (*e.g.*, one movable PCS 70b moves relative to a non-moving PCS 70a) in response to forces applied to the at least one photonic crystal structure 20. In the embodiment schematically illustrated by Figure 24, the PCSs 70a, 70b of the photonic crystal structure 20 are illuminated by light emitted from the fiber core 52 of the optical fiber 50. When the PCSs 70a, 70b move vertically with respect to one another, the frequency (and the corresponding wavelength) of the sharp optical resonances supported by the photonic crystal structure 20 shift due to the changed optical coupling between the guided resonances of the individual PCSs 70a, 70b. This shift results in a change of the intensity or the phase of the light reflected from or transmitted through the photonic crystal structure 20 and provides an observable quantity to measure the relative displacement between the two PCSs 70a, 70b.

[0104] In certain embodiments, the housing 30 comprises a structure 210 comprising one or more supports 212 and a movable portion 220. The housing 30 further comprises a coupler 230 configured to be coupled to the optical fiber 50. The movable portion 220 is mechanically coupled to the coupler 230 by the one or more supports 212. The optical fiber 50 of certain embodiments passes through an opening in the coupler 230 and the fiber core 52 is in proximity to and is optically coupled with the photonic crystal structure 20.

[0105] Example materials for the structure 210, the movable portion 220, and the supports 212 include, but are not limited to, crystalline silicon, polysilicon, silica, silicon nitride, ceramics, plastics, amorphous diamond, germanium, indium phosphide, gallium arsenide, and metals and metal alloys. Example materials for the coupler 230 include, but are not limited to, crystalline silicon, Pyrex glass, quartz, polysilicon, silica, silicon nitride, ceramics, plastics, amorphous diamond, germanium, indium phosphide, gallium arsenide, and metals and metal alloys.

[0106] In certain embodiments, the coupler 230 comprises an optically transmissive portion 232 (*e.g.*, a hole, a window, an optically transmissive membrane)

through which the optical fiber 50 emits light to irradiate the photonic crystal structure 20. The optically transmissive portion 232 allows light emitted by the fiber core 52 to irradiate the photonic crystal structure 20, and allows light reflected by the photonic crystal structure 20 to be received by the fiber core 52.

[0107] The movable portion 220 is configured to move (*e.g.*, as denoted by the double-headed arrow in Figure 24) in response to the pressure modulations of an acoustic wave 40 incident on the movable portion 220. In the embodiment schematically illustrated by Figure 24, one PCS 70a (*e.g.*, the PCS closer to the optical fiber 50) is generally stationary, while the other PCS 70b (*e.g.*, the PCS farther from the optical fiber 50) is attached to the movable portion 220 of the structure 210. In certain other embodiments, the PCS 70b is generally stationary while the PCS 70a is attached to the movable portion 220.

[0108] In certain embodiments, the movement of the PCS 70b has a component in a direction substantially perpendicular to the PCS 70a, wherein the movement changes a distance between the PCSs 70a, 70b. In the embodiment schematically illustrated by Figure 24, the PCS 70b attached to the structure 210 will simultaneously move in response to an incident acoustic wave 40, such that the acoustic wave 40 modulates the distance between the two PCSs 70a, 70b. In this way, the reflectivity (*e.g.*, the power of the reflected light) and/or the transmissivity (*e.g.*, the power of the transmitted light) of the photonic crystal structure 20 is modulated by the incident acoustic wave 40. The optical signal reflected from the photonic crystal structure 20 is transmitted back to the optical fiber 50 and directed to a detector (not shown), which measures the reflected signal power. In certain embodiments, the phase of the reflected light is measured instead of the power of the reflected light. In certain embodiments, the movement of the PCS 70b has a component in a direction substantially parallel to the PCS 70a.

[0109] In certain embodiments, the sensitivity (*e.g.*, the change of the detected reflected power per unit of incident acoustic pressure) of the photonic crystal structure 20 is advantageously increased by utilizing a signal having a frequency (or wavelength) offset slightly from one of the resonance frequencies (or wavelengths) of the double-PCS photonic crystal structure 20. In certain embodiments utilizing extremely high sensitivities, the PCSs

70a, 70b are designed to have extremely sharp resonances, *e.g.*, by breaking a mirror symmetry of at least one of the PCSs 70a, 70b, as described herein.

[0110] In certain embodiments, the mechanical properties of the acoustic sensor structure 200 (*e.g.*, mechanical resonance frequency, spring constant) are dependent on both the movable portion 220 of the structure 210 and the one or more supports 212. In certain embodiments, the movable portion 220 serves as the mechanical spring by providing a restoring force in response to displacements of the movable portion 220 by acoustic waves 40. In certain other embodiments, the supports 212 serve as the mechanical spring by providing the restoring force in response to displacements of the movable portion 220 by acoustic waves 40. Other embodiments utilizing other spring designs for the structure 210 or the supports 212 are also compatible with embodiments described herein.

[0111] In certain embodiments, the acoustic sensor system 200 is insensitive to static pressure variations in the medium (*e.g.*, seawater) in which it operates. As an example, the acoustic sensor system 200 of certain embodiments is operable close to the surface of seawater, or several feet below the surface of seawater. In certain embodiments, the housing 30 comprises at least one pressure conduit 240 between an inner region 250 within the housing 30 and an outer region 260 outside the housing 30. In certain embodiments, the at least one pressure conduit 240 comprises the movable portion 220 of the housing 30. In certain such embodiments, the movable portion 220 comprises an elastic membrane that is responsive to a pressure differential between the inner region 250 and the outer region 260 by moving to remove the pressure differential. In certain embodiments, the supports 210 provide the restoring force to the movable portion 220 and are responsive to a pressure differential across the movable portion by moving the movable portion 220 to reduce the pressure differential. The at least one pressure conduit 240 of certain embodiments serves as low-pass filters that equalize the static pressure between the inner region 250 and the outer region 260.

[0112] In certain embodiments, the at least one pressure conduit 240 comprises a hole through the housing 30, with the hole fluidly coupling the inner region 250 with the outer region 260. In certain such embodiments, the inner region 250 is filled with the same medium (*e.g.*, seawater) of the acoustic waves 40 as is the outer region 260, and the medium is free to flow between the inner region 250 and the outer region 260. In certain

embodiments, the at least one pressure conduit 240 comprises a hole through the housing 30 and an elastic membrane that seals the at least one pressure conduit 240 to fluidly isolate the inner region 250 from the outer region 260. The membrane of certain embodiments is responsive to a pressure differential between the inner region 250 and the outer region 260 by moving to reduce the pressure differential, thereby still acting as a low-pass filter equalizing the pressure inside and outside the acoustic sensor system 200, while keeping the medium (*e.g.*, seawater) from entering the acoustic sensor system 200. In certain such embodiments in which it is desirable to not expose the photonic crystal structure 20 or other internal components of the acoustic sensor system 200 to the medium (*e.g.*, seawater) which can be corrosive and dirty, the membrane advantageously keeps the medium of the acoustic waves 40 from entering the inner region 250 within the housing 30. Example materials for the membrane include, but are not limited to, silicon nitride or rubber.

[0113] In certain embodiments, the acoustic sensor system 200 includes other structural components for better performance and reliability. These other structural components are not crucial for the operation of the acoustic sensor system 200. In certain embodiments, the acoustic sensor system 200 comprises one or more spacers 270 positioned to avoid contact between the two PCSs 70a, 70b in response to a large-magnitude pressure wave incident on the acoustic sensor system 200, thereby advantageously avoiding stiction between the two PCSs 70a, 70b. The spacers 270 of certain embodiments serve as safety structures which define a minimum separation between the two PCSs 70a, 70b, thereby preventing the two PCSs 70a, 70b from contacting and sticking to each other. Example materials for the spacers 270 include, but are not limited to, crystalline silicon, polysilicon, silicon nitride, silicon oxide, amorphous diamond, ceramics, plastics, germanium, indium phosphide, gallium arsenide, and metals and metal alloys. In certain embodiments, amorphous diamond is used because it is hydrophobic which facilitates the prevention of sticking of the two PCSs 70a, 70b.

[0114] Due to the sensitivity of the optical properties of the photonic crystal structure 20 on the medium surrounding the PCSs 70a, 70b, in certain embodiments, the medium in which the acoustic sensor system 200 is placed (*e.g.*, water) is advantageously restricted from the region 280 within the acoustic sensor system 200. In certain such

embodiments, the PCSs 70a, 70b of the photonic crystal structure 20 operate within a gas (*e.g.*, air). In certain embodiments, the housing 30 defines a region (*e.g.*, inner region 250) comprising a liquid and external to the at least one photonic crystal structure 20 and defines the region 280 containing the at least one photonic crystal structure 20 and that is substantially free of the liquid. While liquid may be able to intrude into the region 280 through the opening under the spacers 270, in certain embodiments, both the pressure of the gas inside the region 280 and the small size of the openings under the spacers 270 are selected to advantageously prevent intrusion of the liquid into the region 280, which could otherwise degrade the operation of the acoustic sensor system 200. Certain embodiments advantageously improve the liquid expulsion out of the region 280 further by providing at least a portion of the photonic crystal structure 20 with a hydrophobic surface configured to restrict the liquid from the region 280.

[0115] Figure 25 schematically illustrates an example acoustic sensor system 200 comprising a secondary housing 310. The secondary housing 310 of certain embodiments is mechanically coupled to the housing 30 and contains a non-corrosive liquid or gas, including but not limited to, deionized water, isopropanol, or air. Certain such embodiments advantageously protect various components of the acoustic sensor system 200 from corrosion or other damage from the medium (*e.g.*, seawater) in which the acoustic waves 40 are being measured.

[0116] In certain embodiments, the secondary housing 310 is sufficiently elastic to equalize the pressure outside and inside the secondary housing 310 such that pressure modulations due to the incident acoustic wave 40 are translated into the medium (*e.g.*, gas or fluid) within the secondary housing 310. In certain such embodiments, the secondary housing 310 comprises a balloon. In certain other embodiments, the secondary housing 310 comprises a rigid portion and an elastic membrane.

[0117] Figure 26 schematically illustrates another example acoustic sensor system 200 having a secondary housing 310 which protects the photonic crystal structure 20 within the secondary housing 310. In certain embodiments, the photonic crystal structure 20 is sealed within the secondary housing 310 with a clean, non-corrosive, and non-damaging liquid or gas in the inner region 250 and in the outer region 260. In certain such

embodiments, the movable PCS 70b of the photonic crystal structure 20 is directly on the movable portion 220 of the housing 30.

[0118] Figure 27 schematically illustrates an example acoustic sensor system 200 comprising a photonic crystal structure 20 comprising a single PCS 70. The acoustic sensor system 200 further comprises a metal layer 320 that is at least partially transmissive and at least partially reflective to light emitted by the optical fiber 50. In certain embodiments, the metal layer 320 is a metal coating on the end of the optical fiber 50. In certain embodiments, the PCS 70 and the metal layer 320 form a Fabry-Perot interferometric cavity that is sensitive to displacements of the PCS 70 relative to the metal layer 320. In certain embodiments, the metal layer 320 comprises a thin adhesion layer (*e.g.*, chromium or titanium layer with a thickness of about 4 nanometers) on the optical fiber 50, and a gold or silver layer on the adhesion layer and having a thickness in a range between about 5 nanometers and about 50 nanometers. In certain other embodiments, the metal layer 320 comprises an aluminum layer on the optical fiber 50 and having a thickness in a range between about 5 nanometers and about 50 nanometers. In certain other embodiments, other metals and metal alloys can be used. In certain embodiments, utilizing the metal layer 320 simplifies the fabrication process of the device.

[0119] Figure 28 schematically illustrates an example acoustic sensor system 200 comprising a photonic crystal structure 20 comprising a single PCS 70. The acoustic sensor system 200 further comprises a Bragg grating at or near the end of the optical fiber 50. In certain embodiments, the Bragg grating comprises a grating deposited at or near the end of the optical fiber 50 and that is a few micrometers thick. In certain other embodiments, as schematically illustrated by Figure 28, the Bragg grating comprises a fiber Bragg grating 330 which is part of the optical fiber 50. The fiber Bragg grating 330 is at least partially transmissive and at least partially reflective to light emitted by the optical fiber 50. In certain embodiments, the PCS 70 and the fiber Bragg grating 330 form a Fabry-Perot interferometric cavity that is sensitive to displacements of the PCS 70 relative to the fiber Bragg grating 330. Typically, fiber Bragg gratings have a pitch of several hundred nanometers and a total length ranging from several hundred micrometers to several millimeters. The fiber Bragg grating of certain embodiments provides a reflectivity from a few percent up to almost 100% in a

wavelength bandwidth ranging from picometers up to several nanometers. The optical properties of such combinations of a single PCS 70 and a fiber Bragg grating 330 are described more fully below. Fiber Bragg gratings 330 compatible with certain embodiments described herein are commercially available and use of such fiber Bragg gratings can simplify fabrication of the acoustic sensor system 200.

[0120] Figure 29 schematically illustrates a perspective view of an example configuration of an acoustic sensor system 200 coupled to one end of an optical fiber 50. The acoustic sensor system 200 comprises a housing 30 having a structure 210 with a movable portion 220 and pressure conduits 240 (*e.g.*, holes) and a coupler 230. Other configurations of the acoustic sensor system and the optical fiber are also compatible with embodiments described herein.

[0121] Certain embodiments of the acoustic sensor system 200 described herein provide various advantages over standard fiber-based sensor systems. In certain embodiments, the acoustic sensor system 200 advantageously achieves higher frequency operation due to the flexibility provided by MEMS fabrication technology. In certain such embodiments, the acoustic sensor system 200 is designed to operate at frequencies larger than 10 kHz, a range that is inaccessible for present-day acoustic fiber sensor systems, and in certain embodiments, can operate at frequencies up to about 50 kHz. In certain embodiments, the PCS-based acoustic sensor system described herein is advantageously more sensitive at higher frequencies than are present-day acoustic fiber sensor systems. In certain embodiments, the acoustic sensor system 200 advantageously provides high sensitivity (*e.g.*, sensitive to less than 30 micropascals/Hz^{1/2}). In certain embodiments, the acoustic sensor system 200 comprises a photonic crystal structure 20 that can be fabricated on substrates (*e.g.*, chips) using lithography techniques (as described more fully below), thereby facilitating mass production and low cost, and that is fiber-compatible. In certain embodiments, utilizing MEMS fabrication technology to fabricate the acoustic sensor system 200 advantageously results in acoustic sensor systems that are small in size, light, and compact. In certain embodiments, the compactness of the PCS-based acoustic sensor systems described herein advantageously facilitates their deployment. In certain embodiments, the PCS-based acoustic sensor systems described herein can be

advantageously designed to be insensitive to the polarization of the incident light, thereby eliminating the need for compensation for polarization-induced signal fading.

Fabrication

[0122] In certain embodiments, surface micromachining techniques and bulk micromachining techniques are used in the fabrication process flow to form various components of the acoustic sensor system 200. Lithography techniques compatible with embodiments described herein include, but are not limited to, optical lithography, electron-beam lithography, nano-imprinting techniques, and other techniques generally compatible with microelectromechanical system (MEMS) fabrication. Surface micromachining techniques compatible with embodiments described herein include, but are not limited to, film deposition, dry etching, wet etching, epitaxial growth, wafer bonding, and sacrificial releasing. Bulk micromachining techniques compatible with embodiments described herein include, but are not limited to, anisotropic or isotropic deep reactive ion etching, anisotropic wet etching using KOH (potassium hydroxide) or TMAH (tetramethylammonium hydroxide), and isotropic wet etching.

[0123] Figures 30A-30Q schematically illustrate an example fabrication process flow compatible with certain embodiments described herein for the components of the acoustic sensor system 200. Many other fabrication process flows, with different process steps, number of process steps, and/or order of process steps are also compatible with certain embodiments described herein, and the choice of which process flow to use is typically dependent on the types of equipment that are available for use. As schematically illustrated by Figure 30A, the starting material for fabrication is a silicon-on-insulator (SOI) wafer 500 having a substrate 510 with a (100) crystal orientation and a thickness of about 500 microns, an oxide layer 520 over the substrate 510 with a thickness of about 1 micron, and a silicon layer 530 over the oxide layer 520 with a thickness of about 10 microns. Other materials for the wafer 500 are also compatible with certain embodiments described herein.

[0124] As schematically illustrated by Figure 30B, the SOI wafer 500 is oxidized to form an oxide layer 540 over the silicon layer 530 and having a thickness of about 1 micron. As schematically illustrated by Figure 30C, the oxide layer 540 is patterned by etching the oxide layer 540 down to the silicon layer 530 (e.g., by using a first mask) to

isolate various portions of the oxide layer 540 from one another. As schematically illustrated by Figure 30D, portions of the oxide layer 540 are further etched (*e.g.*, by using a second mask) by about 500 nanometers.

[0125] As schematically illustrated by Figure 30E, the silicon layer 530 is etched down to the oxide layer 520. As schematically illustrated by Figure 30F, the oxide layer 540 is etched down by about 500 nanometers, thereby removing portions of the oxide layer 540. As schematically illustrated by Figure 30G, portions of the silicon layer 530 are etched down by about 5 microns. As schematically illustrated by Figure 30H, the oxide layer 540 is removed.

[0126] As schematically illustrated by Figure 30I, a silicon wafer 600 having an oxide layer 610 on at least one side is bonded to the SOI wafer 500 with the oxide layer 610 in contact with the silicon layer 530. In certain embodiments, the oxide layer 610 has a thickness of about 10 microns. In certain embodiments, the side of the silicon wafer 600 that is not in contact with the silicon layer 530 is polished or grinded down to produce a silicon layer 620 having a thickness of about 10 microns on top of the oxide layer 610.

[0127] As schematically illustrated by Figure 30J, the silicon layer 620 is patterned to make alignment marks visible and to form MEMS structures. In certain embodiments, this patterning includes using a third mask and etching the silicon layer 620 down to the oxide layer 610.

[0128] As schematically illustrated by Figure 30K, an oxide layer 630 is formed on the silicon layer 620 (*e.g.*, deposited and patterned using a fourth mask and etching with hydrogen fluoride) and an oxide layer 632 is formed on the silicon layer 510. In certain embodiments, each of the oxide layer 630 and the oxide layer 632 has a thickness of about 2 microns. As schematically illustrated by Figure 30L, another oxide layer 640 is formed on the oxide layer 630 and on the exposed portions of the silicon layer 620 and another oxide layer 642 is formed on the oxide layer 632. In certain embodiments, each of the oxide layer 640 and the oxide layer 642 has a thickness of about 2 microns.

[0129] As schematically illustrated by Figure 30M, the SOI wafer 500 is patterned (*e.g.*, using a fifth mask) by etching an aperture 650 through the oxide layer 642, the oxide layer 632, and the silicon layer 510, stopping at the oxide layer 520. As schematically

illustrated by Figure 30N, the aperture is extended by etching away a portion of the oxide layer 520, stopping at the silicon layer 530, and the oxide layer 640 is etched away. In certain embodiments, the etching of the oxide layer 642, the oxide layer 632, the silicon layer 530, the oxide layer 520, and the oxide layer 640 are performed during the same etching step. In certain embodiments, the resultant structure is separated into individual chips, and the subsequent process steps are performed on the chip scale.

[0130] As schematically illustrated by Figure 30O, a controlled etch of a portion of the silicon layer 530 through the aperture 650 is performed (*e.g.*, the aperture 650 self-aligns and masks the silicon layer 530) and a controlled etch of a portion of the silicon layer 620 through a portion of the oxide layer 630 is performed. In certain embodiments, the remaining portion of the silicon layer 530 has a thickness of about 450 nanometers and the remaining portion of the silicon layer 620 has a thickness of about 450 nanometers. These remaining portions serve as the silicon substrates for the photonic crystal slabs 70a, 70b of the acoustic sensor system 200. In certain embodiments, the oxide layer 632 is removed.

[0131] As schematically illustrated by Figure 30P, the lattice of the photonic crystal structure 20 is formed by patterning (*e.g.*, by PMMA coating, electron-beam exposure, etching, and stripping resist) to form the two photonic crystal slabs 70a, 70b and the oxide layer 610 is removed, as schematically illustrated by Figure 30Q. In certain embodiments, the two PCSs 70a, 70b are self-aligned with the same geometrical parameters. To avoid detrimental stress effects due to the oxide layer 610 underneath the portion 670 resulting from the silicon layer 530, in certain embodiments, hydrofluoric acid can be used to remove the oxide layer 610 from portions of the membrane before the lattice is patterned. For defining the lattice, a Raith150 electron-beam lithography tool can be used. In certain embodiments, the primary masking material for transferring the photonic crystal lattice onto the membrane is a monolayer of 496,000 relative molecular mass polymethylmethacrylate (PMMA), a high resolution, high current positive resist. The exposed patterns are developed in a 1:2 solution of methyl isobutyl ketone : isopropyl alcohol and then anisotropically etched with a plasma etcher, using a plasma of SF₆ and CHClF₂, resulting in near 90° sidewalls. A single masking material gives reproducible and well-resolved structures. In certain

embodiments, the size of the individual photonic crystal slabs 70a, 70b is about 100 microns x 100 microns. A similar fabrication method can be adapted for other materials such as silicon nitride or silicon oxide.

[0132] In certain embodiments, to create 100 micron x 100 micron free-standing silicon PCSs 70a, 70b, 808-micron-wide square apertures 650 are formed on the back of the SOI wafer 500 using anisotropic etching to etch through the 500-micron-thick substrate 510. Using an anisotropic etchant of 30% KOH in water with 1% isopropyl alcohol to reduce surface tension, well-defined structures with smooth etched surfaces can be achieved.

Analysis of the mechanics of a diaphragm

[0133] The mechanics of the movable portion 220 and of the elastic portions (e.g., the secondary housing 310) of the acoustic sensor system 200 affect the performance of various embodiments described herein. These mechanics are analyzed below for various configurations of the acoustic sensor system 200. While the calculations below provide some insight into the operation of various embodiments described herein, but are not intended to be limiting.

A. Free vibration of a diaphragm

[0134] The equation of motion for the transverse displacement u of a stretched diaphragm with thickness h , and density ρ can be expressed as:

$$\left(h\rho \frac{\partial^2}{\partial t^2} + D\nabla^4 - h\sigma\nabla^2 \right) u = 0 \quad (1)$$

(See, e.g., I. Ladabaum *et al.*, "Surface micromachined capacitive ultrasonic transducers," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions, vol. 45, issue 3, pages 678-690 (May 1998); and M. Yu, "Fiber-Optic Sensor Systems for Acoustic Measurements," Ph.D. Dissertation, University of Maryland, College Park, MD.) Here σ is the residual stress and D is the flexural rigidity, defined as:

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad (2)$$

where E is the Young's modulus, and ν is Poisson's ratio. It should be noted that equation (1) is only applicable for small transverse displacements. When the deflection is large, the equation becomes non-linear.

[0135] For a clamped circular diaphragm with radius a , assuming a solution $u(r, \theta, t) = u(r, \theta)e^{j\omega t}$, equation (1) becomes:

$$D\nabla^4 u - h\sigma\nabla^2 u = h\rho\omega^2 u \quad (3)$$

which has a solution of the form:

$$u(r, \theta) = [AJ_m(\alpha r) + BI_m(\beta r)]\cos(m\theta) \quad (4)$$

where $J_m()$ is the Bessel function of the first kind of order m , and $I_m()$ is the modified Bessel function of the first kind of order m , with

$$\alpha^2 = \frac{\sqrt{h^2\sigma^2 + 4\rho hD\omega^2} - h\sigma}{2D} \quad \text{and} \quad \beta^2 = \frac{\sqrt{h^2\sigma^2 + 4\rho hD\omega^2} + h\sigma}{2D}. \quad (5)$$

The boundary conditions state that $u(a, \theta) = 0$, and $\frac{\partial}{\partial r}u(a, \theta) = 0$. These conditions reduce to the eigenvalue equation:

$$J_m(\alpha a)\frac{d}{dr}I_m(\beta a) - I_m(\beta a)\frac{d}{dr}J_m(\alpha a) = 0 \quad (6)$$

that can be solved together with equations (5), which can be summarized as:

$$(\beta a)^2 - (\alpha a)^2 = \kappa^2 \quad (7)$$

where κ is the useful “tension parameter” defined as $\kappa = a\sqrt{h\sigma/D}$.

[0136] The solutions to equations (6) and (7) for each $m = 0, 1, 2, \dots$ can be denoted as α_{mn} and β_{mn} , where $n = 1, 2, 3, \dots$ denotes the n^{th} root. The boundary conditions give the eigenmodes as:

$$u_{mn}(r, \theta) = C \left[J_m(\alpha_{mn}r) - \frac{J_m(\alpha_{mn}a)}{I_m(\beta_{mn}a)} I_m(\beta_{mn}r) \right] \cos(m\theta) \quad (8)$$

where the eigenfrequency of a mode is found through equations (5) as:

$$\omega_{mn} = \alpha_{mn}\beta_{mn}\sqrt{\frac{D}{h\rho}} \quad (9)$$

B. Forced oscillation of a diaphragm

[0137] For a forced and damped diaphragm, the equation of motion becomes:

$$\left(h\rho \frac{\partial^2}{\partial t^2} + b \frac{\partial}{\partial t} + D\nabla^4 - h\sigma\nabla^2 \right) u = P(r, \theta, t) \quad (10)$$

where b is the damping coefficient, and P is the pressure applied on the diaphragm surface. In the case of a miniature microphone, where $\lambda_{acoustic} \gg a$, the pressure wave will be a plane wave, hence $P(r, \theta, t) = P(t) = P_0 e^{j\omega t}$.

[0138] Due to the similarity to the free vibration problem, we expect a solution of the form:

$$u(r, \theta, t) = \sum_{m,n} A_{mn}(t) u_{mn}(r, \theta) \quad (11)$$

where u_{mn} are the modes from the free vibration problem, and A_{mn} are modal participation factors. Putting equation (11) into equation (10) provides the following:

$$\sum_{m,n} \left[u_{mn} \left(h\rho \frac{\partial^2 A_{mn}}{\partial t^2} + b \frac{\partial A_{mn}}{\partial t} \right) + A_{mn} (D\nabla^4 u_{mn} - h\sigma \nabla^2 u_{mn}) \right] = P_0 e^{j\omega t} \quad (12)$$

The second term on the left-hand-side is given by equation (3). Hence, equation (12) becomes:

$$\sum_{m,n} \left(h\rho \frac{\partial^2 A_{mn}}{\partial t^2} + b \frac{\partial A_{mn}}{\partial t} + h\rho \omega_{mn}^2 A_{mn} \right) u_{mn} = P_0 e^{j\omega t} \quad (13)$$

To solve this equation, the orthogonality of the eigenmodes can be exploited, which is:

$$\int_0^{2\pi} \int_0^a u_{mn} u_{kl} r dr d\theta = \delta_{mk} \delta_{nl} \int_0^{2\pi} \int_0^a u_{mn}^2 r dr d\theta \quad (14)$$

Using the orthogonality, the left-hand-side in equation (13) becomes:

$$\left(h\rho \frac{\partial^2 A_{mn}}{\partial t^2} + b \frac{\partial A_{mn}}{\partial t} + h\rho \omega_{mn}^2 A_{mn} \right) \int_0^{2\pi} \int_0^a u_{mn}^2 r dr d\theta$$

while the right-hand-side becomes:

$$P_0 e^{j\omega t} \int_0^{2\pi} \int_0^a u_{mn}(r, \theta) r dr d\theta = P_0 e^{j\omega t} \int_0^a u_{mn}(r) r dr \int_0^{2\pi} \cos(m\theta) d\theta$$

Since

$$\int_0^{2\pi} \cos(m\theta) d\theta = \begin{cases} 2\pi, & m = 0 \\ 0, & m \neq 0 \end{cases},$$

the incident pressure wave only couples to modes with $m = 0$, the modes that have only radial nodes (no polar nodes). Therefore, the index m can be dropped, so that only the index n is used.

[0139] In this case, the eigenvalue equation (6) reduces to:

$$\frac{\alpha_n}{\beta_n} = -\frac{J_0(\alpha_n a)}{J_1(\alpha_n a)} \cdot \frac{I_1(\beta_n a)}{I_0(\beta_n a)} \quad (15)$$

And the eigenmodes in equation (8) become:

$$u_n(r) = C \left[J_0(\alpha_n r) - \frac{J_0(\alpha_n a)}{I_0(\beta_n a)} I_0(\beta_n r) \right] \quad (16)$$

The equation for the modal participation factor A_n becomes then:

$$\frac{\partial^2 A_n}{\partial t^2} + \frac{\omega_n}{Q_n} \frac{\partial A_n}{\partial t} + \omega_n^2 A_n = \frac{U_n}{h\rho} P_0 e^{j\omega t} \quad (17)$$

where $Q_n = h\rho\omega_n/b$ is the quality factor of the n^{th} mode, and the constant U_n is:

$$U_n = \frac{\int_0^a u_n r dr}{\int_0^a u_n^2 r dr}$$

[0140] Assuming a solution of the form $A_n(t) = A_n e^{j(\omega t + \phi_n)}$, equation (17) gives:

$$A_n(t) = \frac{U_n P_0 e^{j\omega t}}{h\rho(\omega_n^2 - \omega^2 + j\omega\omega_n/Q_n)} \quad (18)$$

Hence, we get the displacement as:

$$u(r, t) = \sum_n A_n(t) u_n(r) = P_0 e^{j\omega t} \sum_n \frac{U_n u_n(r)}{h\rho(\omega_n^2 - \omega^2 + j\omega\omega_n/Q_n)} \quad (19)$$

This is the general solution for any frequency. For low frequencies, such that $\omega \ll \omega_n$:

$$u(r, t) = P_0 e^{j\omega t} \sum_n \frac{U_n u_n(r)}{h\rho\omega_n^2 \left(1 + j \frac{1}{Q_n} \frac{\omega}{\omega_n} \right)} \quad (20)$$

This is a general solution for the transverse displacement of a stretched diaphragm that is vibrated by a pressure plane wave at a frequency below resonance.

C. Solutions for the special cases of membrane and plate

[0141] Two different kinds of structures, which are diaphragms made of silicon-nitride and crystalline-silicon, are of interest. Due to the mechanical properties of these two materials, the diaphragm solutions have closed forms as is discussed below.

C.1 Membrane solution

[0142] A membrane is a diaphragm where the residual stress is dominant, *e.g.* $\kappa \rightarrow \infty$. The membrane structure is a good approximation for $\kappa > 20$, which is the case for a silicon-nitride diaphragm that usually has a high residual stress. In this case, since $\beta_n \rightarrow \kappa/a \rightarrow \infty$, the eigenvalue equation (15) becomes simply $J_0(\alpha_n a) = 0$. For notational simplicity, $\alpha_n a = z_n$, where z_n denotes the n^{th} zero of $J_0(x)$.

[0143] Also, the eigenmodes in equation (16) become $u_n(r) = C J_0(z_n r/a)$, so that:

$$U_n u_n(r) = \frac{\int_0^a J_0(z_n r/a) r dr}{\int_0^a J_0^2(z_n r/a) r dr} J_0(z_n r/a) = \frac{2}{z_n} \cdot \frac{J_0(z_n r/a)}{J_1(z_n)}$$

The eigenfrequencies in equation (9), on the other hand, become:

$$\omega_n = \frac{z_n}{a} \sqrt{\frac{\sigma}{\rho}}$$

Using these in the general solution of equation (20):

$$u(r,t) = P_0 e^{j\omega t} \frac{2a^2}{h\sigma} \sum_n \frac{1}{z_n^3} \cdot \frac{J_0(z_n r/a)}{J_1(z_n)} \left(1 + j \frac{\omega b a^2}{h\sigma} \cdot \frac{1}{z_n^2} \right)^{-1} \quad (21)$$

[0144] To find a closed form of this expression, two different damping conditions, which are $b = 0$, and $b \rightarrow \infty$ will be considered.

C.1.a Membrane solution - negligible damping case

[0145] For $b = 0$, the displacement in equation (21) becomes:

$$u(r,t) = P_0 e^{j\omega t} \frac{2a^2}{h\sigma} \sum_n \frac{1}{z_n^3} \cdot \frac{J_0(z_n r/a)}{J_1(z_n)}$$

which can be recognized as a Fourier-Bessel series. A function in the interval $x = (0,1)$ can be expanded in a Fourier-Bessel series as:

$$f(x) = \sum_n C_n J_0(z_n x)$$

where the coefficients C_n are given as:

$$C_n = \frac{2}{J_1^2(z_n)} \int_0^1 f(x) J_0(z_n x) x dx$$

[0146] Considering the integral

$$\int_0^1 (1-x^2) J_0(z_n x) x dx = \frac{4J_1(z_n)}{z_n^3},$$

the displacement for negligible damping in a closed form can be expressed as:

$$u(r, t) = P_0 e^{j\omega t} \frac{a^2}{4h\sigma} \left(1 - \frac{r^2}{a^2} \right) \quad (22)$$

This solution is also consistent with other reports. See, e.g., W.P. Eaton *et al.*, "A new analytical solution for diaphragm deflection and its application to a surface micromachined pressure sensor," Int'l Conf. on Modeling and Simulation of Microsystems, 1999. Note that equation (22) is an exact solution applicable to the whole range of $r = (0, a)$.

C.1.b Membrane solution - strong damping case

[0147] For $b \rightarrow \infty$, the displacement in equation (21) becomes:

$$u(r, t) = P_0 e^{j\omega t} \frac{2}{j\omega b} \sum_n \frac{1}{z_n} \cdot \frac{J_0(z_n r/a)}{J_1(z_n)}$$

[0148] Considering the integral

$$\int_0^1 J_0(z_n x) x dx = \frac{J_1(z_n)}{z_n},$$

the displacement for strong damping in a closed form can be expressed as:

$$u(r, t) = P_0 e^{j\omega t} \frac{1}{j\omega b} \quad (23)$$

Therefore, when the damping is very strong, the membrane tends to move as a whole without a noticeable bending.

C.2 Plate solution

[0149] A plate is a diaphragm where the bending stiffness is dominant, *e.g.* $\kappa = 0$. The plate structure is a good approximation for $\kappa < 2$, which is the case for a crystalline-silicon diaphragm that usually has very low residual stress.

[0150] In this case, since $\beta_n = \alpha_n$, the eigenvalue equation (15) becomes:

$$J_0(\alpha_n a) + \frac{J_1(\alpha_n a)}{I_1(\alpha_n a)} I_0(\alpha_n a) = 0$$

For notational simplicity, $\alpha_n a = z_n$, where z_n denotes the n^{th} zero of the function $\mathfrak{J}_0(x)$ that is defined as:

$$\mathfrak{J}_0(z_n r/a) = J_0(z_n r/a) + \frac{J_1(z_n)}{I_1(z_n)} I_0(z_n r/a)$$

Whence, the eigenmodes in equation (16) become $u_n(r) = C \mathfrak{J}_0(z_n r/a)$, so that:

$$U_n u_n(r) = \frac{\int_0^a \mathfrak{J}_0(z_n r/a) r dr}{\int_0^a \mathfrak{J}_0^2(z_n r/a) r dr} \mathfrak{J}_0(z_n r/a) = \frac{2}{z_n} \cdot \frac{J_1(z_n)}{J_0^2(z_n)} \mathfrak{J}_0(z_n r/a)$$

[0151] The eigenfrequencies in equation (9), on the other hand, become:

$$\omega_n = \frac{z_n^2}{a^2} \sqrt{\frac{D}{h\rho}}$$

Using these in the general solution of equation (20):

$$u(r, t) = P_0 e^{j\omega t} \frac{2a^4}{D} \sum_n \frac{1}{z_n^5} \cdot \frac{J_1(z_n)}{J_0^2(z_n)} \mathfrak{J}_0(z_n r/a) \left(1 + j \frac{\omega b a^4}{D} \cdot \frac{1}{z_n^4} \right)^{-1} \quad (24)$$

To find a closed form of this expression, two different damping conditions, which are $b = 0$, and $b \rightarrow \infty$ are considered.

C.2.a Plate solution - negligible damping case

[0152] For $b = 0$, the displacement in equation (24) becomes:

$$u(r, t) = P_0 e^{j\omega t} \frac{2a^4}{D} \sum_n \frac{1}{z_n^5} \cdot \frac{J_1(z_n)}{J_0^2(z_n)} \mathfrak{J}_0(z_n r/a)$$

It is possible to define a generalized Fourier-Bessel series for the function $\mathfrak{I}_0(x)$, using the orthogonality of $\mathfrak{I}_0(z_n x)$, which is:

$$\int_0^1 \mathfrak{I}_0(z_n x) \mathfrak{I}_0(z_m x) x dx = \delta_{nm} J_0^2(z_n)$$

Using this orthogonality, a function in the interval $x = (0,1)$ can be expanded as:

$$f(x) = \sum_n C_n \mathfrak{I}_0(z_n x)$$

Where the coefficients C_n are given in this case as:

$$C_n = \frac{1}{J_0^2(z_n)} \int_0^1 f(x) \mathfrak{I}_0(z_n x) x dx$$

Calculation shows that

$$\int_0^1 (1-x^2)^2 \mathfrak{I}_0(z_n x) x dx = 64 \frac{2J_1(z_n)}{z_n^5}$$

[0153] Hence, the displacement for negligible damping in a closed form can be expressed as:

$$u(r,t) = P_0 e^{j\omega t} \frac{a^4}{64D} \left(1 - \frac{r^2}{a^2}\right)^2 \quad (25)$$

Note that this is an exact solution applicable to the whole range of $r = (0,a)$. This solution is also consistent with other reports. See, e.g., W.P. Eaton *et al.*, "A new analytical solution for diaphragm deflection and its application to a surface micromachined pressure sensor," Int'l Conf. on Modeling and Simulation of Microsystems, 1999. Also note that the decay from $r = 0$ to $r = a$ is more rapid compared to the membrane case.

C.2.b Plate solution - strong damping case

[0154] For $b \rightarrow \infty$, the displacement in equation (21) becomes:

$$u(r,t) = P_0 e^{j\omega t} \frac{2}{j\omega b} \sum_n \frac{1}{z_n} \cdot \frac{J_1(z_n)}{J_0^2(z_n)} \mathfrak{I}_0(z_n r/a)$$

Calculation shows that

$$\int_0^1 \mathfrak{I}_0(z_n x) x dx = \frac{2J_1(z_n)}{z_n}$$

Hence, the displacement for strong damping in a closed form can be expressed as:

$$u(r, t) = P_0 e^{j\omega t} \frac{1}{j\omega b} \quad (26)$$

Therefore, as in the membrane case, when the damping is very strong, the plate tends to move as a whole without a noticeable bending.

D. Mechanical impedance effects of the surrounding medium

[0155] Calculations of mechanical impedances can facilitate understanding what effect the surrounding medium (such as air or water), and the damping, will have on the displacement of the diaphragm. The mechanical impedance Z is defined as the ratio of pressure to speed, namely $Z = P/v$. In the case discussed here, $v(r) = j\omega u(r)$. To calculate the impedance of the diaphragm, the lumped speed is used, which is:

$$\bar{v} = \frac{1}{\pi a^2} \int_0^a v(r) 2\pi r dr = \frac{2j\omega}{a^2} \int_0^a u(r) r dr$$

so that,

$$Z = \frac{P}{v} = \frac{P_0 e^{j\omega t}}{\bar{v}}.$$

[0156] Using equation (22), the impedance of a diaphragm that can be approximated by a membrane is then:

$$Z_d = \frac{P_0 e^{j\omega t}}{\frac{2j\omega}{a^2} \left(P_0 e^{j\omega t} \frac{a^4}{16h\sigma} \right)} = -j \frac{8h\sigma}{\omega a^2} \quad (27)$$

And similarly, using equation (25), the impedance of a diaphragm that can be approximated by a plate is then:

$$Z_d = \frac{P_0 e^{j\omega t}}{\frac{2j\omega}{a^2} \left(P_0 e^{j\omega t} \frac{a^6}{384D} \right)} = -j \frac{192D}{\omega a^4} \quad (28)$$

The impedance due to the damping will be just $Z_b = b$, as can be verified using equation (23) or equation (26). The fact that the damping impedance is a real number means that it is responsible for dissipation loss in the system.

[0157] To calculate the impedance of the surrounding medium, the expression for the displacement of particles in an acoustic wave can be used:

$$u_a = \frac{1}{\omega \rho_a \nu_a} P_0 e^{j\omega t} \quad (29)$$

where ρ_a is the density of the medium, and ν_a is the speed of the acoustic wave (not to be confused with the speed of the particles that are displaced in the medium). Using equation (29), the impedance of the surrounding medium can be expressed as:

$$Z_s = \frac{P_0 e^{j\omega t}}{j\omega \left(P_0 e^{j\omega t} \frac{1}{\omega \rho_a \nu_a} \right)} = -j \rho_a \nu_a \quad (30)$$

[0158] The total impedance of the system will then be the sum of the impedance of the diaphragm, the damping impedance, and the impedance of the surrounding medium:

$$Z_{total} = Z_d + Z_b + Z_s$$

The total displacement of the diaphragm will depend on the value of this total impedance. If one of the impedances is much larger than the others, the diaphragm displacement will be dominated by it. For example, if the membrane impedance is dominant, *i.e.* $Z_d \gg Z_b, Z_s$, the displacement will be just as in equation (22) or equation (25), the diaphragm displacements under negligible damping. If the damping impedance is dominant, *i.e.* $Z_b \gg Z_d, Z_s$, the displacement will be just as in equation (23) or equation (26), the diaphragm displacements under large damping conditions. And, if the impedance of the surrounding medium is dominant, *i.e.* $Z_s \gg Z_d, Z_b$, the displacement will be just as in equation (29), which is the displacement of the particles in the acoustic wave.

E. Numerical values for the impedances

[0159] As an example system, a circular diaphragm made of either silicon-nitride or crystalline-silicon has the radius of a typical SMF-28 singlemode fiber (*e.g.*, 62.5 microns), and is separated by a distance d from the end of the fiber. Table 1 gives values of various parameters and constants to be used in the calculations.

Table 1:

<i>Parameters and constants</i>
Diaphragm parameters

radius of diaphragm:	$a = 62.5 \text{ microns}$
thickness of diaphragm:	$h = 0.5 \text{ micron}$
gap length between diaphragm and fiber:	$d = 1 \text{ micron}$
operation frequency:	$\omega = 2\pi \times 30 \text{ kHz}$
Silicon-nitride constants	
density:	$\rho_{SiN} = 3270 \text{ kg/m}^3$
estimated residual stress in high stress nitride film:	$\sigma_{SiN} = 300 \text{ MPa}$
Young's modulus:	$E_{SiN} = 320 \text{ GPa}$
Poisson's ratio:	$\nu_{SiN} = 0.26$
Crystalline-silicon constants	
density:	$\rho_{Si} = 2330 \text{ kg/m}^3$
residual stress (estimated to be insignificant):	$\sigma_{Si} \approx 0 \text{ MPa}$
Young's modulus:	$E_{Si} = 150 \text{ GPa}$
Poisson's ratio:	$\nu_{Si} = 0.2$
Air constants	
density (of dry air at 1 atm pressure and 20° C):	$\rho_{air} = 1.21 \text{ kg/m}^3$
speed of sound (at 20° C):	$v_{air} = 343 \text{ m/s}$
dynamic viscosity (at 20° C):	$\mu_{air} = 1.82 \times 10^{-5} \text{ kg/m/s}$
Water constants	
density (of pure water at 20° C):	$\rho_{water} = 998 \text{ kg/m}^3$
speed of sound (in pure water at 20° C):	$v_{water} = 1482 \text{ m/s}$
dynamic viscosity (at 20° C):	$\mu_{water} = 9.77 \times 10^{-4} \text{ kg/m/s}$
density (of sea water with 3.5% salinity at 20° C):	$\rho_{sea-water} = 1025 \text{ kg/m}^3$
speed of sound (in sea water with 3.5% salinity at 20° C):	$v_{sea-water} = 1522 \text{ m/s}$

[0160] Other than the formulas given in the previous sections, an expression can be used to calculate the damping. The calculation of damping is usually complex, and has also a strong dependence on the overall geometry. However, an estimate of the damping can still be made. Because of the close proximity of the diaphragm and the fiber end, the dominant damping will be the squeeze film damping which can be estimated as:

$$b \approx \frac{1}{\pi a^2} \left(0.42 \frac{\mu A^2}{d^3} \right)$$

where μ is the dynamic viscosity of the medium, $A = \pi a^2$ is the area of the plates, and d is the gap length (see, e.g., M. Andrews et al., "A comparison of squeeze-film theory with measurements on a microstructure, Sensors and Actuators A, vol. 36, pages 79–87 (1993)).

[0161] Using the values in Table 1:

$$\begin{aligned} b_{air} &= 9.38 \times 10^4 \text{ kg/m}^2/\text{s}, & \text{damping in air} \\ b_{water} &= 5.04 \times 10^6 \text{ kg/m}^2/\text{s}, & \text{damping in water} \end{aligned}$$

Similarly, using the values in Table 1 in the impedance formulas equations (27), (28), and (30):

$$\begin{aligned} |Z_{SiN}| &= 1.62 \times 10^6 \text{ kg/m}^2/\text{s}, & \text{impedance of a silicon-nitride membrane} \\ |Z_{Si}| &= 1.09 \times 10^5 \text{ kg/m}^2/\text{s}, & \text{impedance of a silicon plate} \\ |Z_{air}| &= 415 \text{ kg/m}^2/\text{s}, & \text{impedance of air} \\ |Z_{water}| &= 1.48 \times 10^6 \text{ kg/m}^2/\text{s}, & \text{impedance of water} \\ |Z_{sea-water}| &= 1.56 \times 10^6 \text{ kg/m}^2/\text{s}, & \text{impedance of sea-water} \end{aligned}$$

[0162] These results show that for the given dimensions, the impedances of the membranes are comparable to the damping and water impedances. A larger diaphragm diameter would yield more advantageous results. A diaphragm radius more than 50% larger would make the silicon-nitride calculations more accurate, since in this case, the tension parameter value of $\kappa \approx 13$ is insufficient to model the nitride diaphragm as a membrane. Also, the damping impedance can be reduced through careful design, such as the size and position of the pressure equalizing holes.

[0163] These results show that the initial assumptions about the displacement of the diaphragm in air and water were inaccurate, and these calculations can be used to make a more optimal sensor design, either for air or water operation.

Fiber Fabry-Perot-based Acoustic Sensor Designs

[0164] The expressions previously derived can be used to find optimal parameters for the acoustic sensor systems. Figure 31 schematically illustrates an example configuration of a movable reflective element (*e.g.*, a membrane) and an optical fiber. The main parameters to be optimized, shown schematically in Figure 31, are the cavity length (L), the radius of the membrane (a), and the reflectivities of the fiber end (R_f) and the membrane mirror (R_m).

[0165] As a first step, the limitations or ranges of these parameters can be calculated. The membrane radius a is preferably equal to at least the radius of the fiber, which is about 62.5 microns, so that the impedance of the membrane does not become excessively large so that it limits the pressure sensitivity of the sensor. The size of the

membrane is preferably sufficiently small to provide a compact and robust sensor. Therefore, the membrane diameter advantageously does not exceed about 300 microns, above which it becomes large and fragile.

[0166] For reasons shown below, the reflectivity of the membrane mirror R_m is preferably as large as possible (e.g., $R_m \sim 1$), which is achieved in certain embodiments with a photonic crystal mirror. The reflectivity of the fiber end (R_f) is preferably as small as possible. The reasons for this are discussed more fully below. Also, a small reflectivity on the fiber end is preferably used, since it is usually difficult to deposit a highly reflective mirror, either metal or dielectric, on the end of a fiber. Also, if a fiber Bragg mirror is used, its length is preferably reduced by requiring a small reflectivity, as it was explained in previous texts.

[0167] To calculate limitations on the cavity length L , several factors are considered. From the mechanical point of view, it is advantageous to have a large length, since this results in a smaller damping. However, when the optical properties are considered, there are certain limitations on the cavity length, as calculated below.

[0168] The contrast of the resonance tends to decrease with increasing mirror reflectivities, so that for very high reflectivities, it appears that there is almost no visible resonance. This effect can be avoided by balancing the mirrors of the Fabry-Perot. In fact, as calculated, full contrast can be restored by having:

$$R_f = R_m 2^{-L/z_0}$$

where $z_0 = \pi w_0^2 n_c / \lambda = k w_0^2 / 2$ is the Rayleigh range, a characteristic length over which the beam does not diverge significantly.

[0169] Also, the maximum sensitivity to displacement occurs at the point where the overall reflection is $R_p = P_r / P_i = 1/2$, on the steeper side of the asymmetric resonance. At that point, the sensitivity is equal to the sensitivity of a regular Fabry-Perot that has an effective reflectivity of:

$$R_{eff} = \sqrt{R_f R_m} = R_m 2^{-L/2z_0}$$

The sensitivity to displacement $\sigma = \partial R_p / \partial L$ of a regular Fabry-Perot at the point $R_p = 1/2$ is calculated as:

$$\sigma = \frac{\pi}{\lambda} \sqrt{K}$$

where $K = 4R_{eff} / (1 - R_{eff})^2$.

[0170] The above relations can be used to calculate the maximum L . This calculated value is dependent on the minimum reflectivity R_{eff} that is used to achieve the required sensitivity. The minimum required reflectivity for the best case scenario corresponds to the noise level being in the shot-noise limit, and the impedance of water being dominant, so that the membrane displaces with the water particles.

[0171] The relations between pressure and water displacement is expressed as:

$$\Delta L = \left(\frac{1}{\omega \nu \rho} \right) \cdot P$$

Using the values $\nu_{water} = 1482 \text{ m/s}$, $\rho_{water} = 998 \text{ kg/m}^3$, and the numbers wanted for the sensor $\omega = 2\pi \times 30 \text{ kHz}$, and $P = 30 \text{ } \mu\text{Pa}/\sqrt{\text{Hz}}$:

$$\Delta L = 1.08 \times 10^{-7} \text{ nm}/\sqrt{\text{Hz}}$$

When the noise level is at the shot-noise limit, then the minimum detectable displacement is:

$$\Delta L_{\min} = \frac{\sqrt{2}}{\pi} \lambda \sqrt{\frac{\Delta f h \nu}{K \eta P_i}}$$

Substituting $\Delta L_{\min}$ with the above number, and using the values, $P_i = 1 \text{ mW}$, $\lambda = 1550 \text{ nm}$, $\eta = 0.9$, and solving for R_{eff} :

$$R_{eff} = 0.954$$

[0172] This is the minimum effective reflectivity to achieve the desired sensitivity under the best conditions. This value can be used to calculate the maximum cavity length. Using the above expression $R_{eff} = R_m 2^{-L/2z_0}$, and requiring that $R_m \sim 1$:

$$L_{\max} = \frac{2z_0}{\ln 2} \ln \left(\frac{R_m}{R_{eff}} \right) = 9.48 \text{ } \mu\text{m}$$

This is the maximum cavity length in water, a limitation imposed by the optical properties of the fiber Fabry-Perot. This number is smaller (7.21 microns) in air, due to the difference in the Rayleigh range, calculated for a regular SMF-28 fiber.

[0173] The other constraint on the cavity length is that it is a multiple of half the operation wavelength, which in certain embodiments is $\lambda = 1550nm$.

[0174] With this knowledge of the limitations for the main parameters: the cavity length (L), the radius of the membrane (a), and the reflectivities of the fiber end (R_f) and the membrane mirror (R_m), the values can be optimized.

[0175] To optimize these parameters, the mechanical properties of the device are considered. In the mechanics calculations, the following impedance values were found for the parameters $a = 62.5 \mu m$ (= radius of an SMF-28 fiber) and $L = 1 \mu m$:

$$\begin{aligned} Z_{water} &= 1.48 \times 10^6 \text{ kg/m}^2/\text{s}, & \text{impedance of water} \\ b_{water} &= 5.04 \times 10^6 \text{ kg/m}^2/\text{s}, & \text{damping in water} \\ Z_{Si} &= 1.09 \times 10^5 \text{ kg/m}^2/\text{s}, & \text{impedance of a silicon plate} \end{aligned}$$

The three impedances are on the same order, which means that the displacement of the membrane will be reduced by a factor f with respect to the displacement of water particles, where:

$$f \approx \frac{Z_{water}}{Z_{water} + b_{water} + Z_{Si}} = 0.22$$

With these impedance values, the membrane will displace only by about 22% of the displacement of the water particles. This number is advantageously closer to about 90% for a sensitive device. To achieve this result, the damping in water, and also possibly, the impedance of the silicon plate are advantageously reduced to have:

$$b_{water} + Z_{Si} \approx 1.64 \times 10^5 \text{ kg/m}^2/\text{s}$$

[0176] The expressions we need to consider are:

$$b_{water} \approx \frac{\mu \pi a^2}{2L^3}, \text{ and } Z_{Si} = \frac{192D}{\omega a^4}$$

To reduce the overall impedance, L can be increased without changing a , since b_{water} has a larger contribution. In such a case, Z_{Si} will remain unchanged, so that advantageously:

$$b_{water} \approx 5.50 \times 10^4 \text{ kg/m}^2/\text{s}$$

Hence, the length is advantageously:

$$L = 1 \mu m \times \left(\frac{5.04 \times 10^6 \text{ kg/m}^2/\text{s}}{5.50 \times 10^4 \text{ kg/m}^2/\text{s}} \right)^{1/3} = 4.51 \mu m$$

[0177] Since the cavity length is a multiple of half the operation wavelength, the closest number to this is $6 \times 1.55 \mu m / 2 = 4.65 \mu m$, which is still within the range of $L_{\max} = 9.48 \mu m$. Using the cavity length $L = 4.65 \mu m$, the reduction factor is $f = 0.9 = 90\%$. Since $a = 62.5 \mu m$ remained unchanged in this calculation, the other two design parameters R_f and R_m remain to be optimized.

[0178] The displacement of the membrane will be:

$$\Delta L \approx f \times \Delta L_{\text{water}} = 0.9 \times 1.08 \times 10^{-7} \text{ nm}/\sqrt{\text{Hz}} = 9.72 \times 10^{-8} \text{ nm}/\sqrt{\text{Hz}}$$

which results in $R_{\text{eff}} = 0.958$ and $R_m = R_{\text{eff}} 2^{L/2z_0} = 0.980$, and $R_f = R_m 2^{-L/z_0} = 0.936$.

[0179] Therefore, a set of parameters for an example design that provides a sensitivity of $30 \mu Pa/\sqrt{\text{Hz}}$ at 30 kHz are: $a = 62.5$ microns, $L = 4.65$ microns, $R_m = 0.980$, and $R_f = 0.936$. Other values are also compatible with certain embodiments described herein.

Fabry-Perot-based Acoustic Sensor Compared to a Fiber Bragg Grating

[0180] A simple Fabry-Perot structure to be employed as an acoustic sensor can be constructed with a photonic crystal mirror and a fiber Bragg grating, (*e.g.*, as shown in Figure 28), or with just two photonic crystal mirrors, as described herein. The sensitivity of such a sensor can be calculated from the basic Fabry-Perot equations. (*See, e.g.*, Thomson *et al.*, "A Fabry-Perot acoustic surface vibration detector-application to acoustic holography," J. Phys. D: Appl. Phys., Vol. 6, page 677 (1973).) In certain embodiments, both of the mirrors forming the Fabry-Perot cavity have a high reflectivity R . Then, for $K = 4R/(1-R)^2$ and $\phi = 2\pi L/\lambda$, with L being the mirror spacing, the relation between the reflected power P_r and the incident power P_i can be calculated as:

$$\frac{P_r}{P_i} = 1 - (1 + K \sin^2 \phi)^{-1} \quad (31)$$

The sensitivity σ to the displacement L will then be:

$$\sigma = \frac{d}{dL} \left(\frac{P_r}{P_i} \right) \quad (32)$$

[0181] To find the maximum sensitivity, equation (32) is solved for $d\sigma/dL = 0$, which is satisfied for $\phi = (3K)^{-1/2} + m\pi$, keeping in mind that $K \gg 1$. This result is expected, stating that the highest sensitivity is at the side of a resonance. Using this value, the maximum sensitivity can be expressed as:

$$\sigma_{\max} = \frac{3\sqrt{3}\pi}{4\lambda} \sqrt{K} \quad (33)$$

Therefore, the maximum sensitivity only depends on the reflectivity of the mirrors, provided that the linewidth of the laser is much smaller than the linewidth of the Fabry-Perot resonance. This condition is satisfied if $L \ll c/\Delta\nu_{\text{laser}}\pi\sqrt{K}$, where $\Delta\nu_{\text{laser}}$ is the linewidth of a single-mode laser (or the frequency spread of a multi-mode laser). Thus, for a sensitive measurement, the linewidth of the laser $\Delta\nu_{\text{laser}}$ is advantageously selected to be much smaller than the linewidth of the Fabry-Perot resonance $\Delta\nu_{F-P} = c/L\pi\sqrt{K}$, which is dependent on the cavity length L . Thus, equation (33) for the maximum sensitivity imposes a limit on the maximum cavity length on the Fabry-Perot cavity depending on the laser linewidth.

[0182] For a sufficiently large laser power such as 1 milliwatt, the dominant noise will be the photodiode shot current. The mean current in the photodiode measuring the reflected power will be $I_0 = P_r e \eta / h\nu$, where η is the quantum efficiency of the photodiode. At the maximum sensitivity point, calculated from equation (31), $P_r = P_i / 4$. This current gives rise to a shot noise current:

$$I_N = \sqrt{2eI_0\Delta f} = \sqrt{\frac{P_i e^2 \eta \Delta f}{2h\nu}}, \quad (34)$$

where Δf is the electronic system bandwidth.

[0183] For a small mirror displacement with peak amplitude ΔL , the signal current in the photodiode will be:

$$I_s = \frac{1}{\sqrt{2}} \frac{\Delta P_r e \eta}{h\nu} \quad (35)$$

and ΔP_r can be calculated using equation (2) to be:

$$\sigma = \frac{1}{P_i} \left(\frac{\Delta P_r}{\Delta L} \right), \quad (36)$$

hence $\Delta P_r = \sigma P_i \Delta L$.

[0184] Operating at maximum sensitivity given in equation (33), the power signal of equation (36) inside the signal current expression of equation (35):

$$I_s = \frac{3\sqrt{3}\pi}{4\sqrt{2}} \left(\frac{\Delta L}{\lambda} \right) \frac{\sqrt{K} e \eta}{h\nu} P_i$$

From which the signal-to-noise ratio can be expressed as:

$$\frac{S}{N} = \frac{I_s^2}{I_N^2} = \frac{27\pi^2}{16} \frac{K\eta P_i}{\Delta f h\nu} \left(\frac{\Delta L}{\lambda} \right)^2 \quad (38)$$

For a unity signal-to-noise ratio, the detection sensitivity of the system will then be:

$$\Delta L_{\min} = \frac{4}{3\sqrt{3}\pi} \lambda \sqrt{\frac{\Delta f h\nu}{K\eta P_i}}. \quad (39)$$

Using the values, $P_i = 1mW$, $\lambda = 1500nm$, $\eta = 0.9$, and a modest reflectivity $R = 0.99$, the value of $\Delta L_{\min} = 2.25 \cdot 10^{-8} nm/\sqrt{Hz}$ is obtained. The sensitivity can be increased through the reflectivity of the mirrors. For example, a reflectivity of $R = 0.999$ provides about 10 times better sensitivity. Throughout the calculations below, the value of $\Delta L_{\min} = 10^{-6} nm/\sqrt{Hz}$ is used, since the experimental values have previously been reported to be about an order of magnitude worse than the theoretical limit.

[0185] The sensitivity given in equation (33) is only dependent on the mirror reflectivity. It may be expected that the length of the cavity would play a crucial role in the sensitivity, so that a much smaller sensitivity would be provided by a long cavity. If equation (33) is written in terms of the cavity length L , and the resonance linewidth $\Delta\nu_{1/2}$:

$$\sigma_{\max} = \frac{3\sqrt{3}}{4\lambda} \left(\frac{c}{\Delta\nu_{1/2} L} \right) \quad (40)$$

which is an expected result. The sensitivity drops with increasing length. Also, as expected, the sensitivity drops with increasing linewidth, since the resonances become less steep. However, in a Fabry-Perot cavity with high reflectivity mirrors, the resonance linewidth is dependent on L , so that the resonances become sharper for longer cavity lengths:

$$\Delta\nu_{1/2} = \frac{c}{\pi\sqrt{K}} \cdot \frac{1}{L} \quad (41)$$

(See, e.g., P. Yeh, “*Optical Waves in Layered Media*,” (Wiley, New York, 1988).) Therefore, the dependence on L in the sensitivity equation (40) cancels out, so that it is the mirror reflectivity provides the dominant contribution (as long as it is high). In certain such embodiments, the important criterion is therefore that the laser linewidth should be much smaller than the Fabry-Perot resonance linewidth.

[0186] To calculate the dynamic range, the minimum detectable length is known, and therefore the maximum length shift is to be calculated. For a Fabry-Perot cavity, $L = \text{constant} \cdot \lambda$, hence:

$$\frac{\Delta L}{L} = \frac{\Delta \lambda}{\lambda} \quad (42)$$

Therefore, the maximum shift is $\Delta L_{\max} = (L/\lambda) \Delta \lambda_{\max}$. The maximum wavelength shift one can detect is one-quarter the linewidth of the Fabry-Perot resonance. Therefore, the maximum detectable cavity length change is, using equation (41):

$$\Delta L_{\max} = \frac{L}{\lambda} \frac{\Delta \lambda_{1/2}}{4} = \frac{\lambda}{4\pi\sqrt{K}} \quad (43)$$

Hence, the dynamic range is:

$$DR = \frac{\Delta L_{\max}}{\Delta L_{\min}} = \frac{3\sqrt{3}}{16} \sqrt{\frac{\eta P_i}{\Delta f h \nu}} \quad (44)$$

which shows that the dynamic range is independent of the Fabry-Perot parameters such as the reflectivity or the cavity length. For the values used above, a dynamic range about 130 dB (20log) results. Again, assuming an order of magnitude less sensitivity ($10^{-6} \text{ nm}/\sqrt{\text{Hz}}$) than that predicted, the dynamic range is then around 110 dB. Although this dynamic range is for the displacement measurements, it also applies for pressure, since the displacement is proportional to the pressure.

[0187] To compare these results to a single fiber Bragg grating, it is desirable to know if it is possible to get the same values by stretching a piece of such a fiber. Figure 32 is a graph of an optical resonance as a function of wavelength. As a first step, the sensitivity for a general sharp resonance is calculated, which is shown in Figure 32. From simple geometrics, we obtain the relation:

$$\frac{\Delta(P_r/P_i)}{\Delta\lambda} \approx \frac{1/2}{\Delta\lambda_{1/2}/2} = \frac{1}{\Delta\lambda_{1/2}} \quad (45)$$

If the resonance wavelength and distance is proportional to each other, as in a Fabry-Perot cavity, so that equation (42) is valid, the sensitivity can be expressed as:

$$\sigma = \frac{\Delta(P_r/P_i)}{\Delta L} = \frac{\lambda/L}{\Delta\lambda_{1/2}} \quad (46)$$

To verify this expression, the expressions for a Fabry-Perot cavity can be used, to get:

$$\sigma = \frac{\pi}{\lambda} \sqrt{K}, \quad (47)$$

which is very close to equation (33), thereby verifying equations (45) and (46).

[0188] Having general expressions for the sensitivity, the sensitivity for a fiber Bragg grating can be calculated. The resonance wavelength of such a structure is:

$$\lambda = 2n_{eff} \frac{L}{N} \quad (48)$$

where n_{eff} is the effective refractive index, L the total length of the grating, and N the number of layers. (See, e.g., Kersey *et al.*, "Fiber grating sensors," J. Lightwave Technol., vol. 15, no. 8, page 1442 (1997).) When such a structure is stretched by ΔL , the wavelength shifts by:

$$\Delta\lambda = 2n_{eff} (0.78) \frac{\Delta L}{N}, \quad (49)$$

where the factor 0.78 comes from changes in the fiber index due to photo-elastic effects. Therefore:

$$\frac{\Delta L}{L} = \frac{1}{0.78} \frac{\Delta\lambda}{\lambda} \quad (50)$$

which shows that equation (42) is valid to that order, meaning equation (46) is also valid to that order. Thus, the sensitivity of a Fabry-Perot cavity and a fiber Bragg grating are on the same order for a given wavelength, provided that $L \cdot \Delta\lambda_{1/2}$ of equation (46) is the same.

[0189] For example, a commercially available fiber Bragg gratings operating at around 1500 nanometers, a linewidth of 0.02 picometer for a grating around 5 centimeters

long, the structure gives $L \cdot \Delta\lambda_{1/2} = 10^3 \text{ nm}^2$. For a Fabry-Perot cavity on the other hand, using equation (11):

$$L \cdot \Delta\lambda_{1/2} = \frac{\lambda^2}{\pi\sqrt{K}} = \frac{\lambda^2}{\pi} \cdot \frac{1-R}{\sqrt{R}} \approx \frac{\lambda^2}{\pi} \cdot (1-R) \quad (51)$$

To get a similar number (e.g., $L \cdot \Delta\lambda_{1/2} = 10^3 \text{ nm}^2$) for a Fabry-Perot cavity, a reflectivity of $R \approx 0.998$ would be used. Hence, such a commercially available fiber Bragg grating seems to have the same sensitivity of a Fabry-Perot cavity with high reflectivity mirrors.

[0190] In this analysis of the Fabry-Perot cavity, it was assumed that the linewidth of the laser is much smaller than the linewidth of the Fabry-Perot resonance. The linewidth of the laser should be one to two orders of magnitude smaller than the resonance linewidth, so that the laser does not average over less sensitive regions. When a small cavity length is used, the Fabry-Perot resonance linewidth is large, hence the laser does not have to be very narrow. When the cavity length is large however, the Fabry-Perot resonance becomes sharper, hence a narrower laser is used to achieve the same sensitivity achieved in a short Fabry-Perot cavity. The main problem arises at this point when the laser has to be extremely narrow.

[0191] Consider the above case for the 0.02 picometer linewidth, for example. To achieve the calculated sensitivity, a laser as narrow as 10^{-3} to 10^{-4} picometer would be used. When a laser is that narrow, other noise sources become dominant over the shot-noise. One of the most important noises for such narrow lasers is the free running frequency noise. In fact, by reducing this noise using a pre-stabilized laser, it was previously experimentally shown that a sensitivity of $10^{-5} \text{ nm}/\sqrt{\text{Hz}}$ can be obtained for a greater than 25 millimeter long Fabry-Perot formed by two fiber Bragg gratings. (See, Chow *et al.*, "Ultra resolution fiber sensor using a pre-stabilized diode laser," page CPDA9, Post-deadline CLEO 2005 (2005).) This reported value is just about an order of magnitude worse than the fundamental shot-noise limited sensitivity for the same structure. Therefore, it is harder to get high sensitivities with long cavity lengths, since in that case a very good laser is used. However, these results should be encouraging for the fiber Bragg grating structure shown in Figure 28, as well as for a Fabry-Perot sensor using two thin photonic crystal slabs as the mirrors.

[0192] Various embodiments have been described above. Although the invention has been described with reference to these specific embodiments, the descriptions are intended to be illustrative of the invention and are not intended to be limiting. Various modifications and applications may occur to those skilled in the art without departing from the scope of the invention as defined in the appended claims.

WHAT IS CLAIMED IS:

1. An acoustic sensor comprising:
 - at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape, the at least one photonic crystal structure comprising at least one photonic crystal slab having a substantially planar configuration;
 - an optical fiber optically coupled to the at least one photonic crystal structure, wherein light emitted from the optical fiber is incident to the at least one photonic crystal structure from a direction substantially perpendicular to the at least one photonic crystal slab; and
 - a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure such that acoustic waves incident upon the housing induce forces applied to the at least one photonic crystal structure that change at least one of the resonance frequency and the resonance lineshape of the at least one optical resonance of the at least one photonic crystal structure.
2. The acoustic sensor of Claim 1, wherein the at least one photonic crystal structure comprises a metal layer between the at least one photonic crystal slab and the optical fiber, the metal layer at least partially transmissive to light emitted by the optical fiber.
3. The acoustic sensor of Claim 2, wherein the metal layer comprises a metal coating on one end of the optical fiber.
4. The acoustic sensor of Claim 3, wherein the metal layer is substantially parallel to the at least one photonic crystal slab.
5. The acoustic sensor of Claim 1, further comprising a fiber Bragg grating.
6. The acoustic sensor of Claim 5, wherein the optical fiber comprises the fiber Bragg grating.
7. The acoustic sensor of Claim 1, wherein the at least one photonic crystal slab comprises a first material and a substantially periodic array of protrusions thereon.
8. The acoustic sensor of Claim 1, wherein a photonic crystal slab of the at least one photonic crystal structure has a thickness and comprises a first material and an array of regions within the photonic crystal slab, each region comprising a second material having a refractive index different from a refractive index of the first material.

9. The acoustic sensor of Claim 8, wherein the array of regions comprises a plurality of holes extending at least partially through the thickness of the photonic crystal slab and containing the second material, the plurality of holes having a substantially periodic distribution within the photonic crystal slab.

10. The acoustic sensor of Claim 9, wherein the first material comprises a solid dielectric material, and the second material comprises air.

11. The acoustic sensor of Claim 9, wherein the first material comprises a solid dielectric material, and the second material comprises water.

12. The acoustic sensor of Claim 9, wherein the array of regions comprises a substantially square array of substantially circular holes.

13. The acoustic sensor of Claim 9, wherein each hole of the plurality of holes has a substantially symmetric shape possessing mirror symmetry with respect to a first axis along the photonic crystal slab and with respect to a second axis along the photonic crystal slab, the second axis substantially perpendicular to the first axis.

14. The acoustic sensor of Claim 9, wherein each hole of the plurality of holes has a substantially asymmetric shape lacking mirror symmetry with respect to a first axis along the photonic crystal slab.

15. The acoustic sensor of Claim 14, wherein each hole of the plurality of holes possesses mirror symmetry with respect to a second axis along the photonic crystal slab, the second axis substantially perpendicular to the first axis.

16. The acoustic sensor of Claim 9, wherein the substantially periodic distribution has a defect.

17. The acoustic sensor of Claim 16, wherein the defect comprises a missing hole, a hole having a different size than the other holes of the plurality of holes, a hole having a different shape than the other holes of the plurality of holes, a hole containing a third material having a refractive index different from the refractive indices of the first material or the second material, or a hole displaced from an expected position of the substantially periodic distribution.

18. The acoustic sensor of Claim 1, wherein the at least one photonic crystal slab is responsive to the forces applied to the at least one photonic crystal slab by stretching, compressing, or bending.

19. The acoustic sensor of Claim 1, wherein the at least one photonic crystal slab comprises a pair of photonic crystal slabs, the pair comprising a first photonic crystal slab

fixedly mounted in the acoustic sensor and a second photonic crystal slab movably mounted in the acoustic sensor, the second photonic crystal slab substantially parallel to the first photonic crystal slab and optically coupled to the first photonic crystal slab, wherein the second photonic crystal slab undergoes movement relative to the first photonic crystal slab in response to the forces applied to the at least one photonic crystal structure.

20. The acoustic sensor of Claim 19, wherein the movement of the second photonic crystal slab has a component in a direction substantially perpendicular to the first photonic crystal slab, the movement changing a distance between the first photonic crystal slab and the second photonic crystal slab.

21. The acoustic sensor of Claim 19, wherein the movement of the second photonic crystal slab has a component in a direction substantially parallel to the first photonic crystal slab.

22. The acoustic sensor of Claim 1, wherein the housing comprises at least one pressure conduit between an inner region within the housing and an outer region outside the housing.

23. The acoustic sensor of Claim 22, wherein the at least one pressure conduit comprises a hole through the housing, the hole fluidly coupling the inner region with the outer region.

24. The acoustic sensor of Claim 22, wherein the at least one pressure conduit comprises an elastic membrane between the inner region and the outer region, the membrane responsive to a pressure differential between the inner region and the outer region by moving to reduce the pressure differential.

25. The acoustic sensor of Claim 22, wherein the at least one pressure conduit comprises a movable portion of the housing between the inner region and the outer region and a support structure mechanically coupled to the movable portion, the support structure providing a restoring force to the movable portion and responsive to a pressure differential across the movable portion by moving the movable portion to reduce the pressure differential.

26. The acoustic sensor of Claim 1, wherein the housing defines a first region containing the at least one photonic crystal structure and a second region external to the at least one photonic crystal structure, wherein the second region comprises a liquid and the first region is substantially free of the liquid.

27. The acoustic sensor of Claim 26, wherein the at least a portion of the housing comprises a hydrophobic surface configured to restrict the liquid from the first region.

28. The acoustic sensor of Claim 26, wherein the first region comprises a gas and the second region comprises water.

29. A method of detecting acoustic waves, the method comprising:

providing a sensor comprising at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape, the at least one photonic crystal structure comprising at least one photonic crystal slab having a substantially planar configuration, the sensor further comprising a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure such that acoustic waves incident upon the housing induce forces applied to the at least one photonic crystal structure that change at least one of the resonance frequency and the resonance lineshape of the at least one optical resonance of the at least one photonic crystal structure;

exposing the sensor to acoustic waves;

irradiating the at least one photonic crystal structure with light from a direction substantially perpendicular to the at least one photonic crystal slab; and

detecting a change of at least one of the resonance frequency and the resonance lineshape induced by the acoustic waves.

30. The method of Claim 29, wherein detecting a change of at least one of the resonance frequency and the resonance lineshape comprises detecting light reflected from the at least one photonic crystal structure, light transmitted through the at least one photonic crystal structure, or both light reflected from the at least one photonic crystal structure and light transmitted through the at least one photonic crystal structure.

31. The method of Claim 30, wherein the at least one photonic crystal structure has a symmetry axis and the light is polarized in a direction substantially perpendicular to the symmetry axis.

32. The method of Claim 30, wherein the at least one photonic crystal structure has a symmetry axis and the light is polarized in a direction substantially parallel to the symmetry axis.

33. The method of Claim 30, wherein the light has a frequency offset from the resonance frequency.

34. The method of Claim 30, wherein the light is emitted by an optical fiber optically coupled to the at least one photonic crystal structure.

35. The method of Claim 30, wherein the at least one photonic crystal slab comprises a photonic crystal slab lacking mirror symmetry with respect to a first axis along the photonic crystal slab.

36. The method of Claim 35, wherein the photonic crystal slab possesses mirror symmetry with respect to a second axis along the photonic crystal slab, the second axis substantially perpendicular to the first axis.

37. An acoustic sensor comprising:

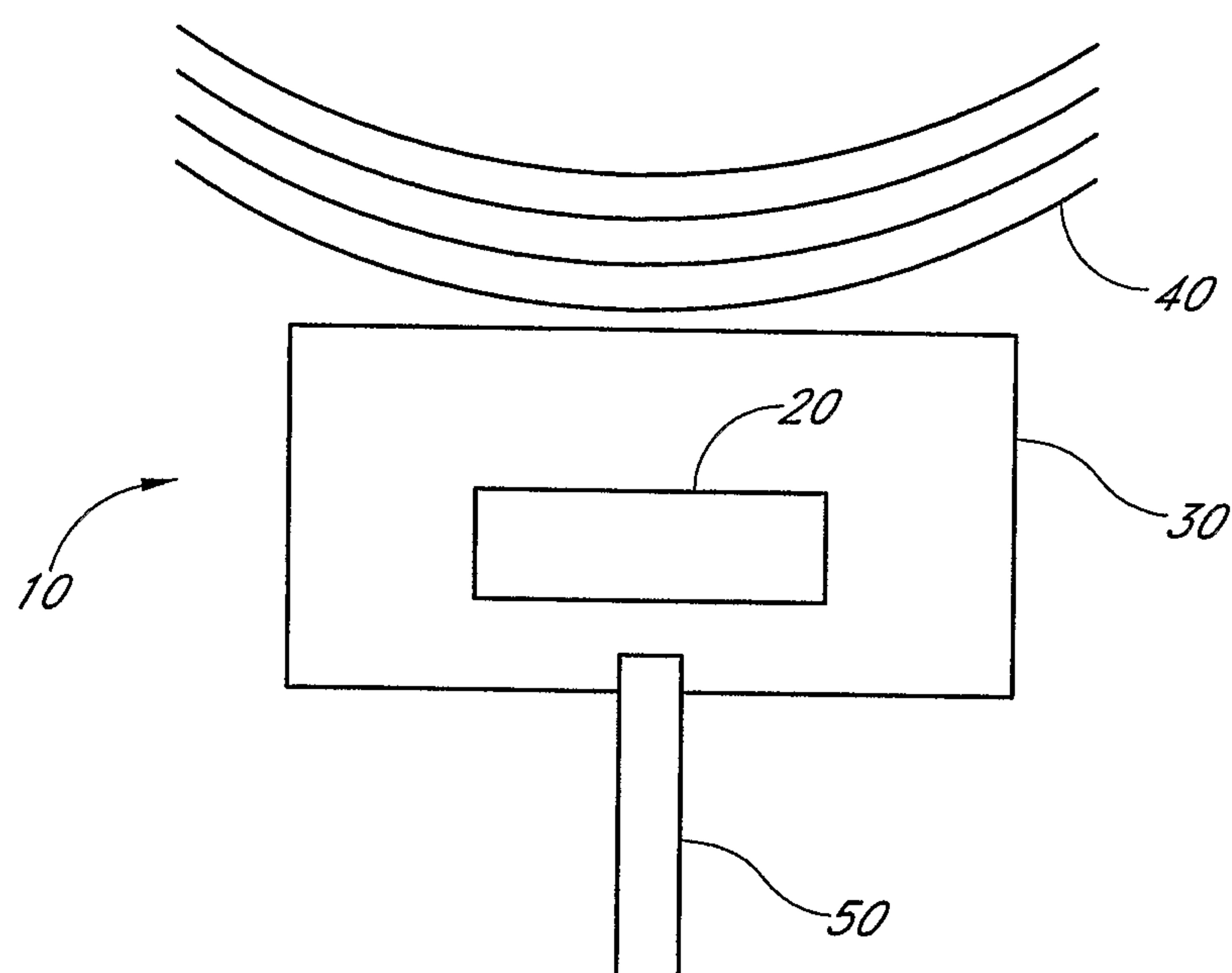
at least one photonic crystal structure having at least one optical resonance with a resonance frequency and a resonance lineshape, the at least one photonic crystal structure comprising at least one photonic crystal slab having a substantially planar configuration;

an optical fiber optically coupled to the at least one photonic crystal structure, wherein light emitted from the optical fiber is incident to the at least one photonic crystal structure in a range of incidence angles within about 10 degrees from a direction substantially perpendicular to the at least one photonic crystal slab; and

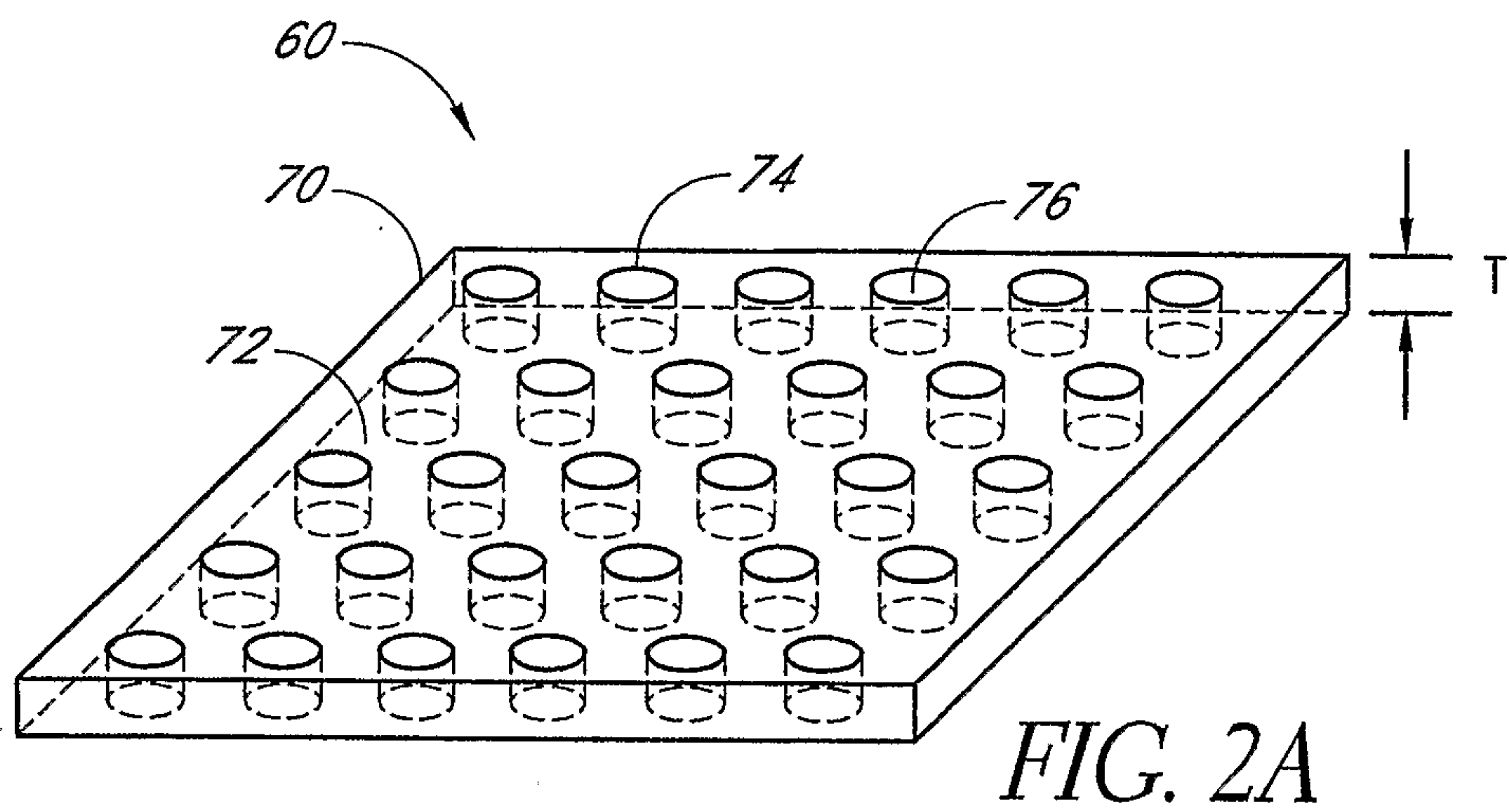
a housing substantially surrounding the at least one photonic crystal structure and mechanically coupled to the at least one photonic crystal structure such that acoustic waves incident upon the housing induce forces applied to the at least one photonic crystal structure that change at least one of the resonance frequency and the resonance lineshape of the at least one optical resonance of the at least one photonic crystal structure.

38. The acoustic sensor of Claim 37, wherein the light is not collimated between being emitted from the optical fiber and reaching the at least one photonic crystal structure.

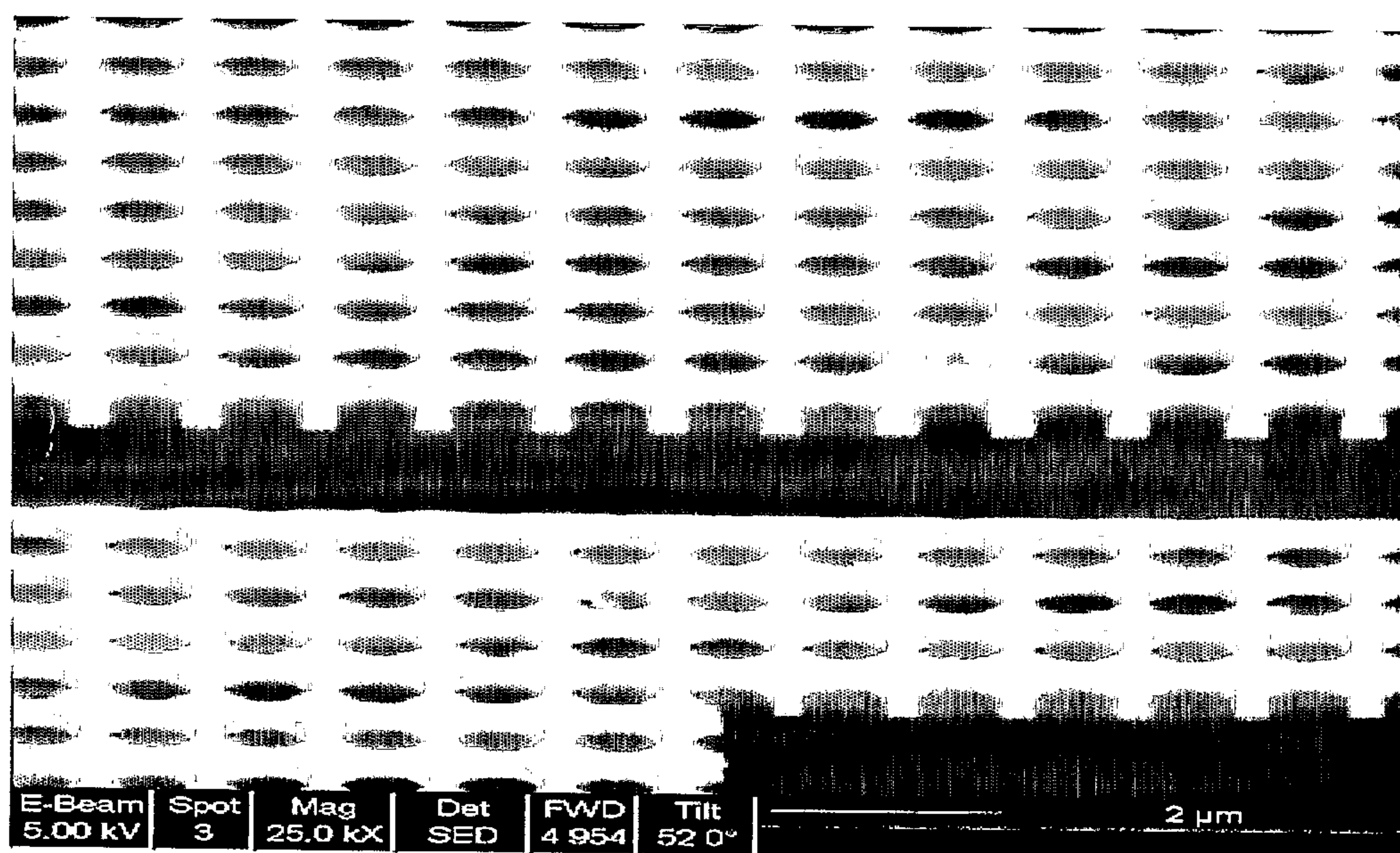
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*FIG. 1*

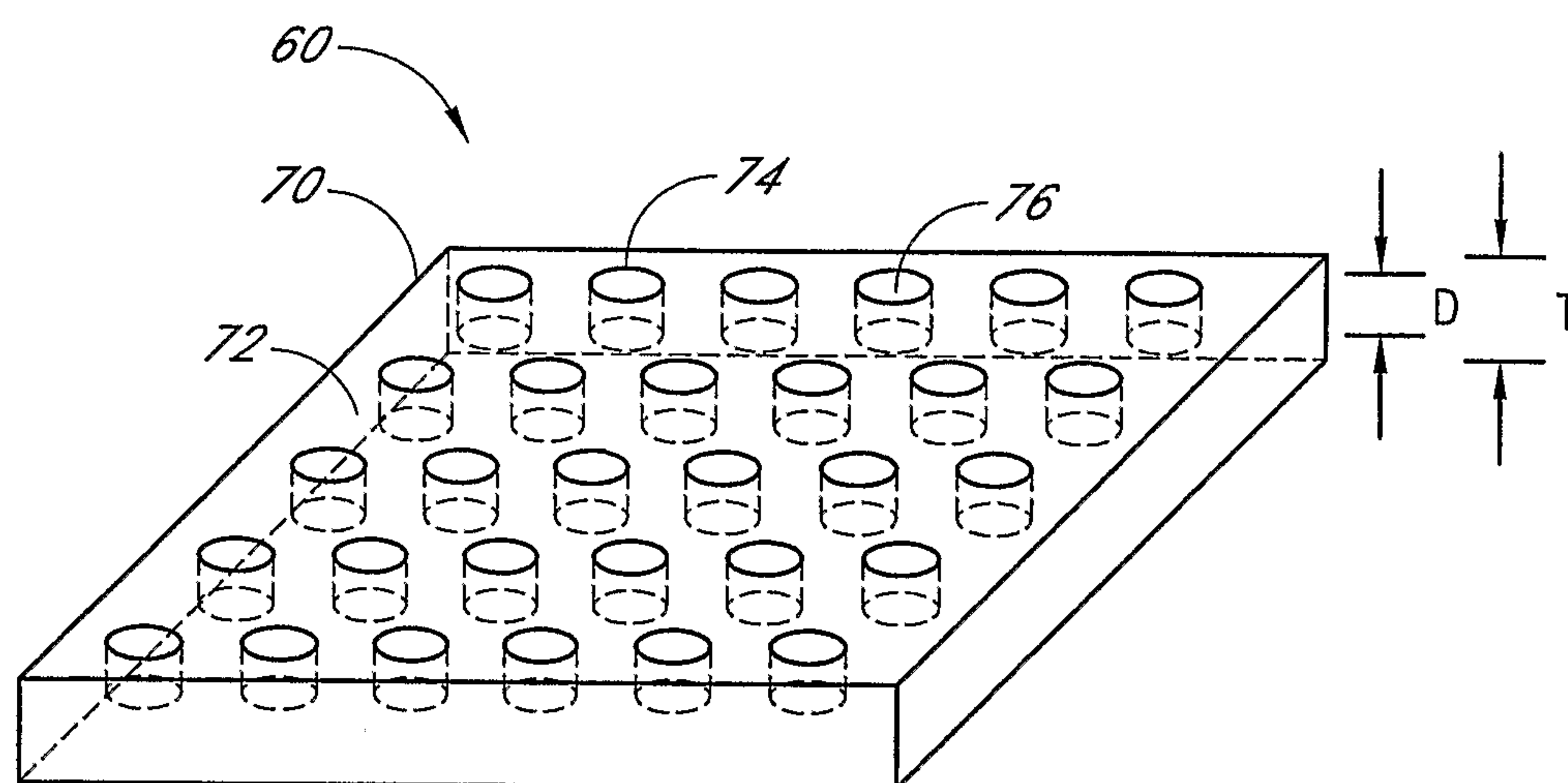
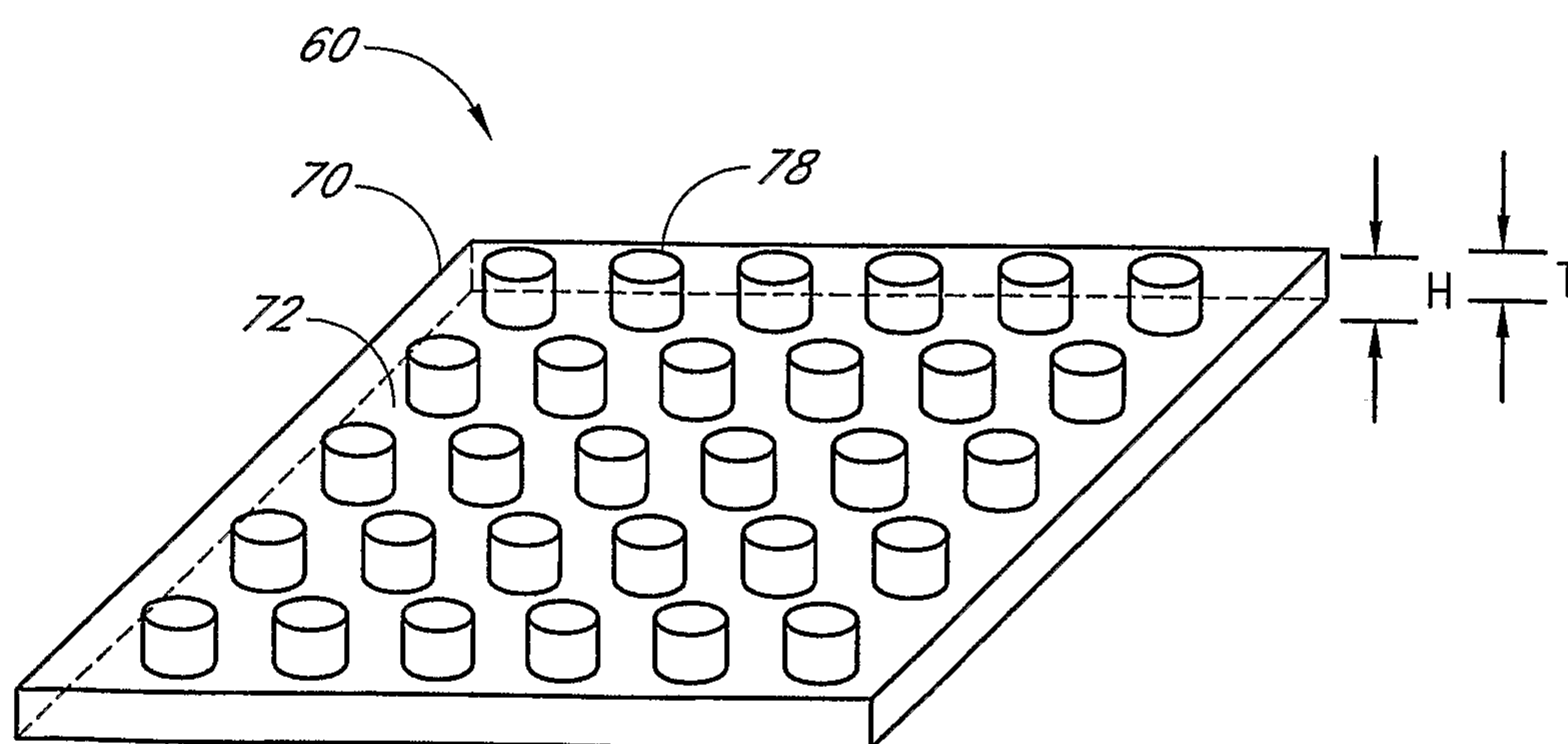
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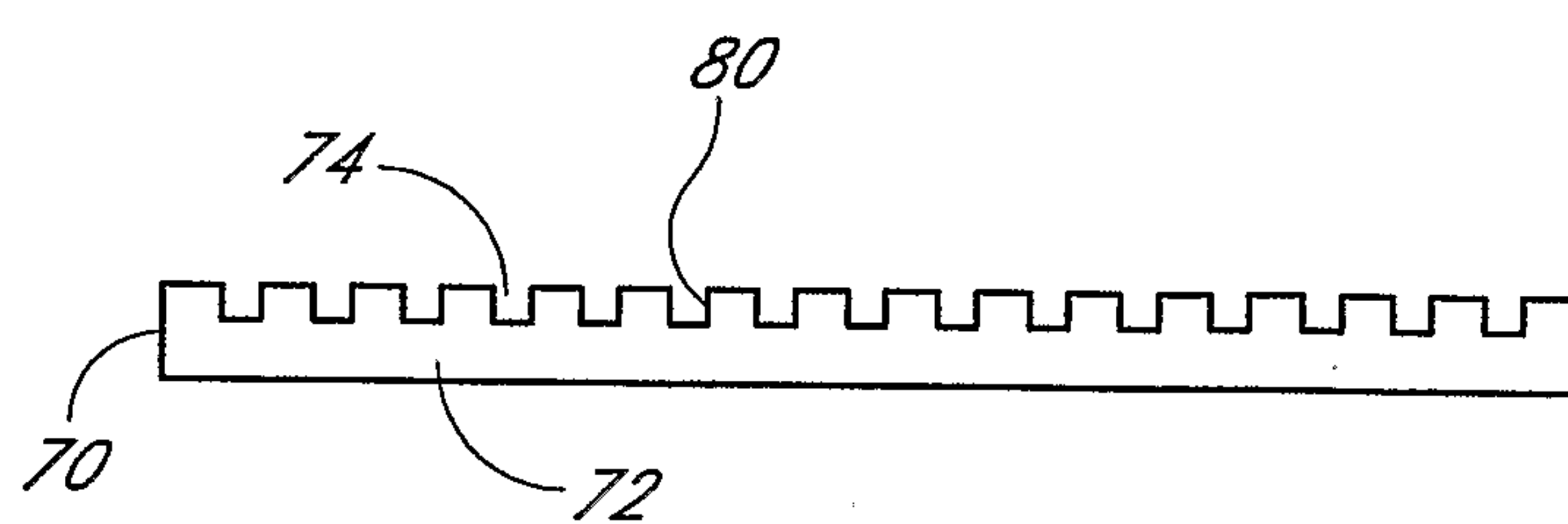
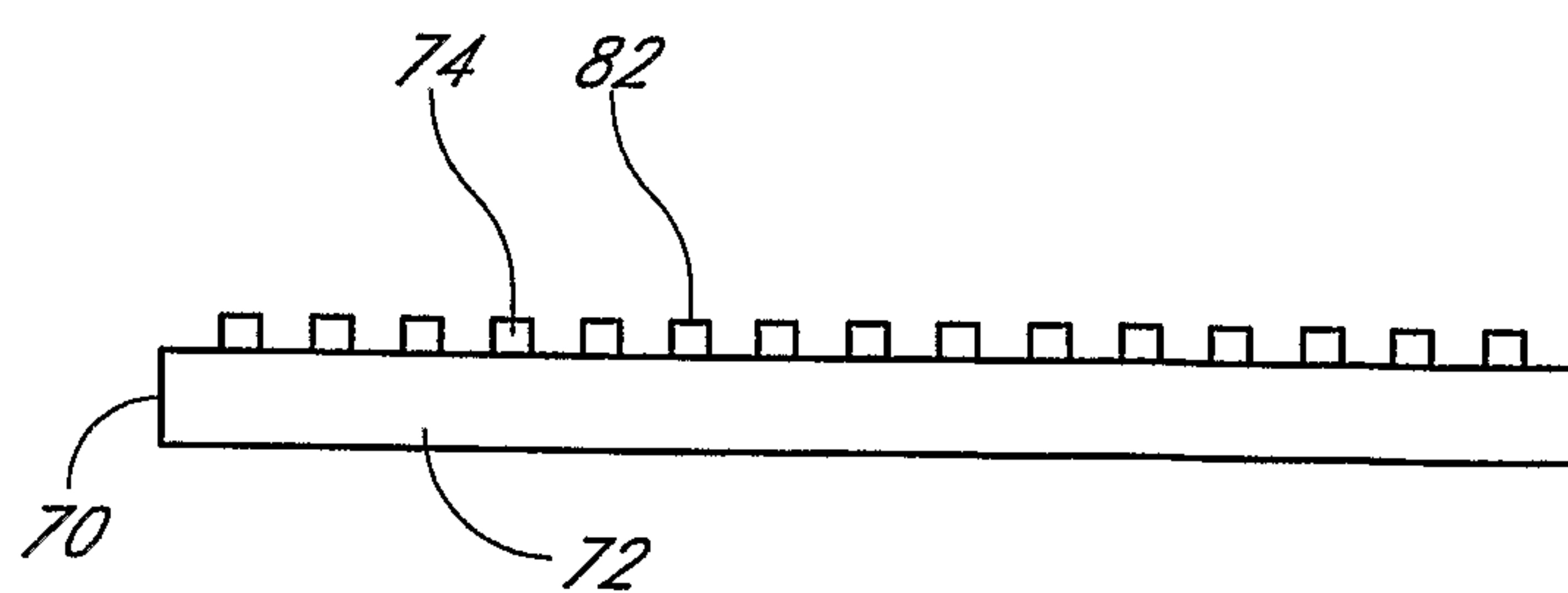
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*FIG. 2B*

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*FIG. 2C**FIG. 2D*

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*FIG. 2E**FIG. 2F*

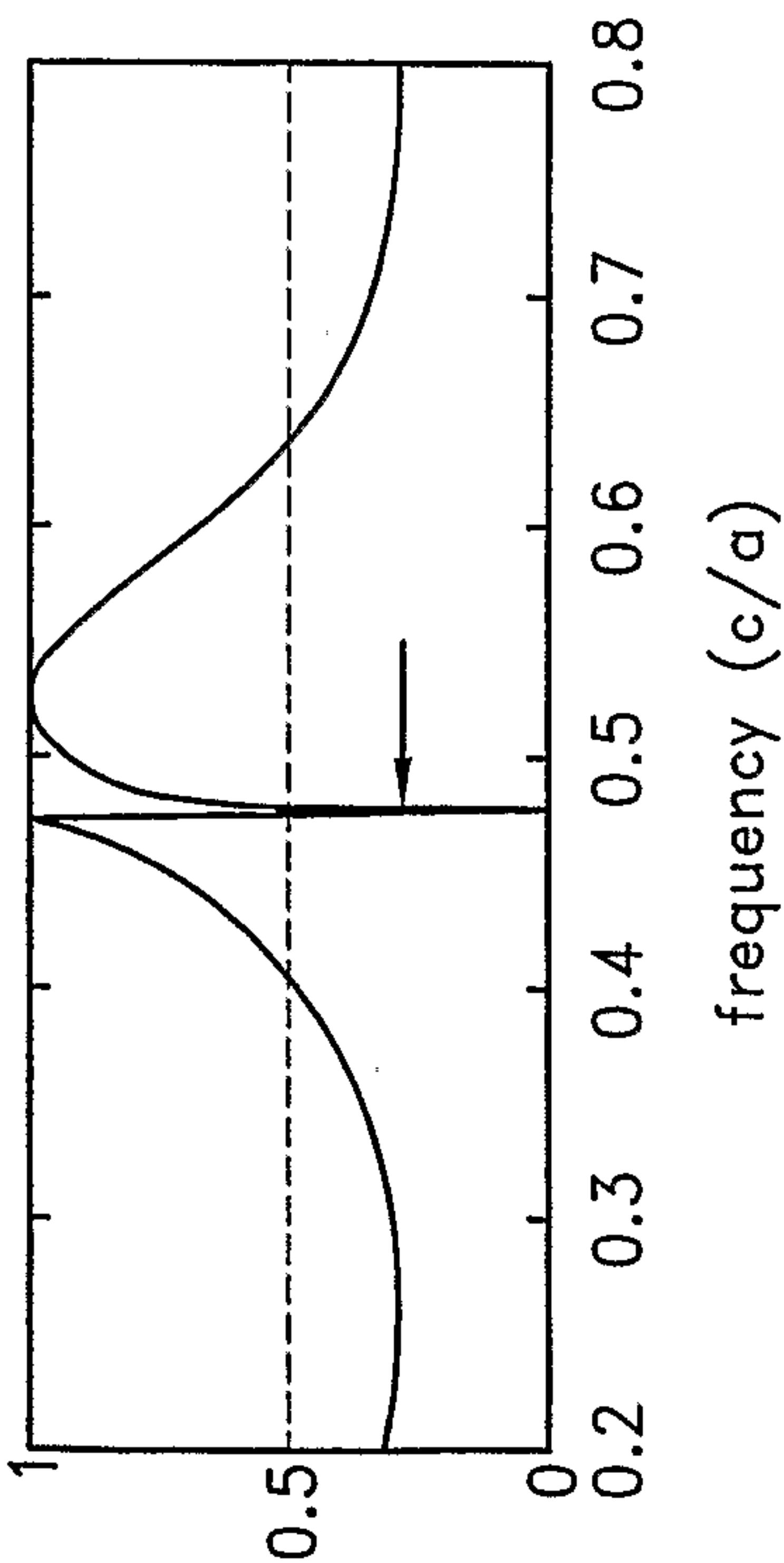
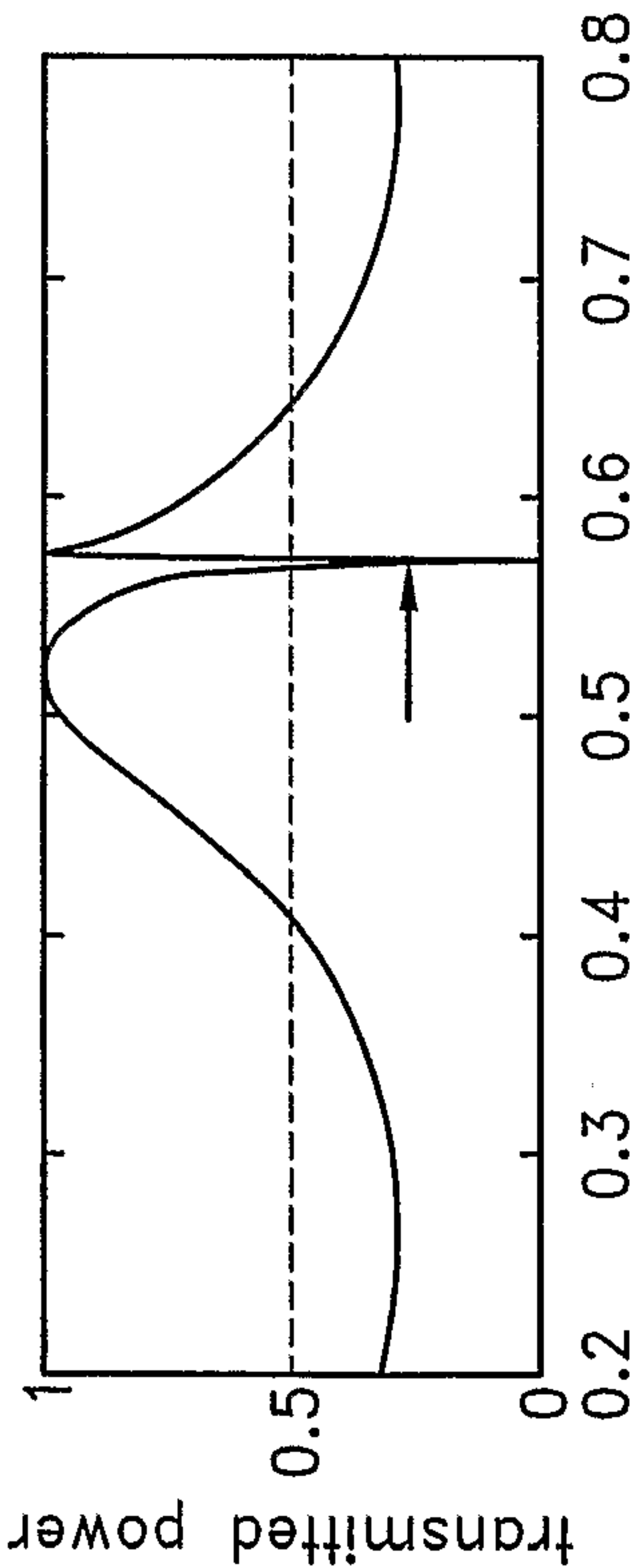
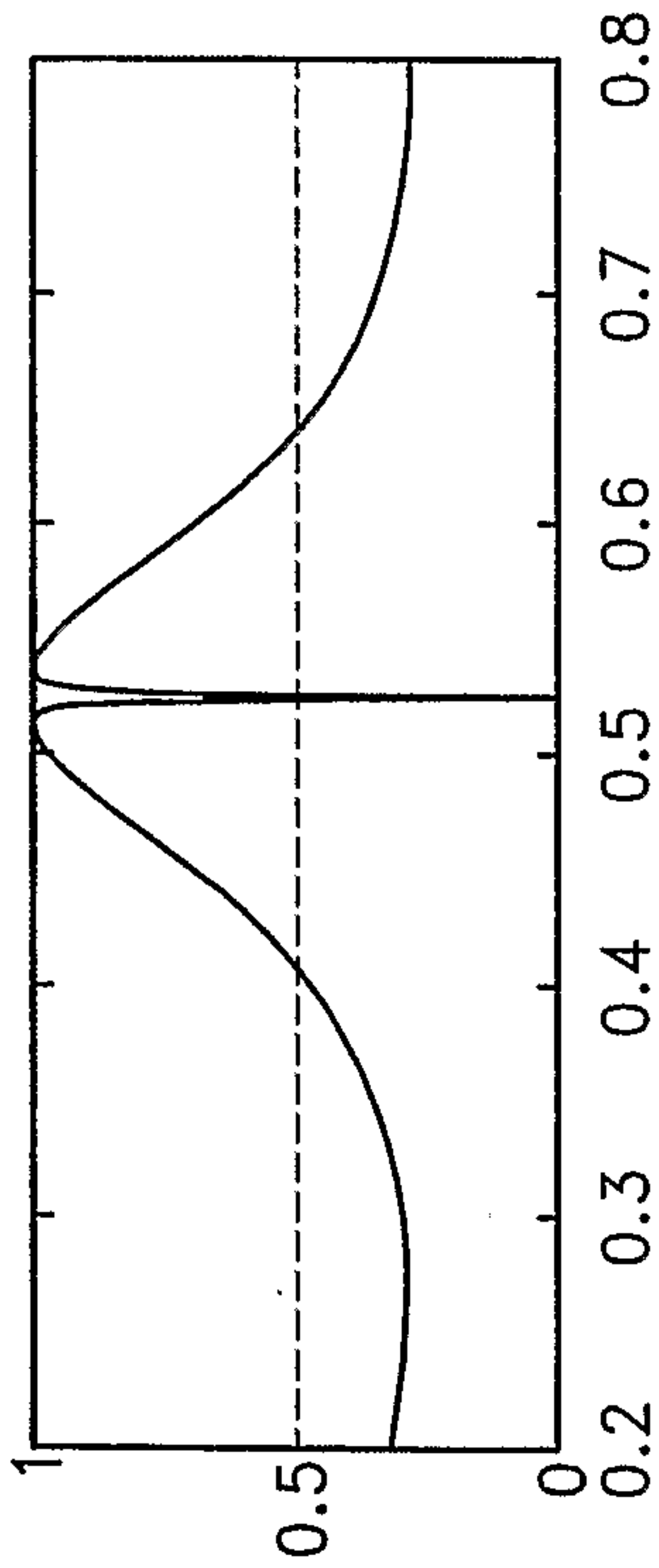
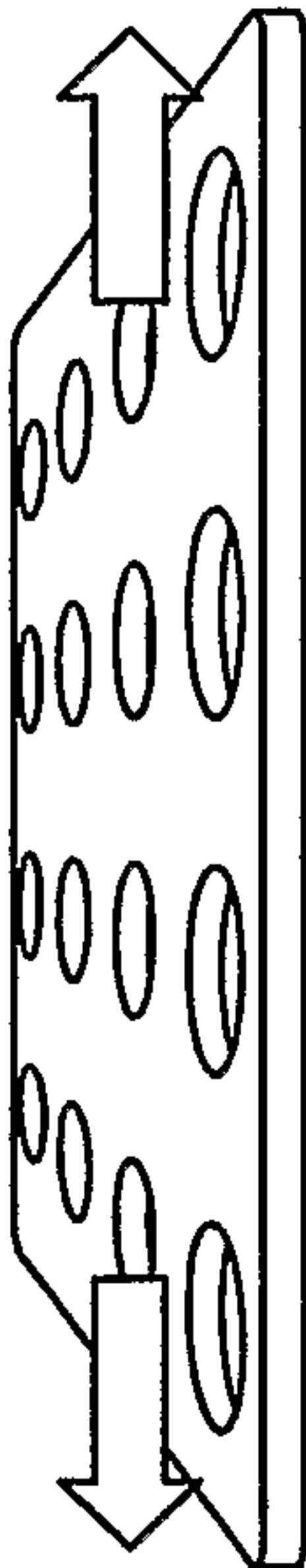
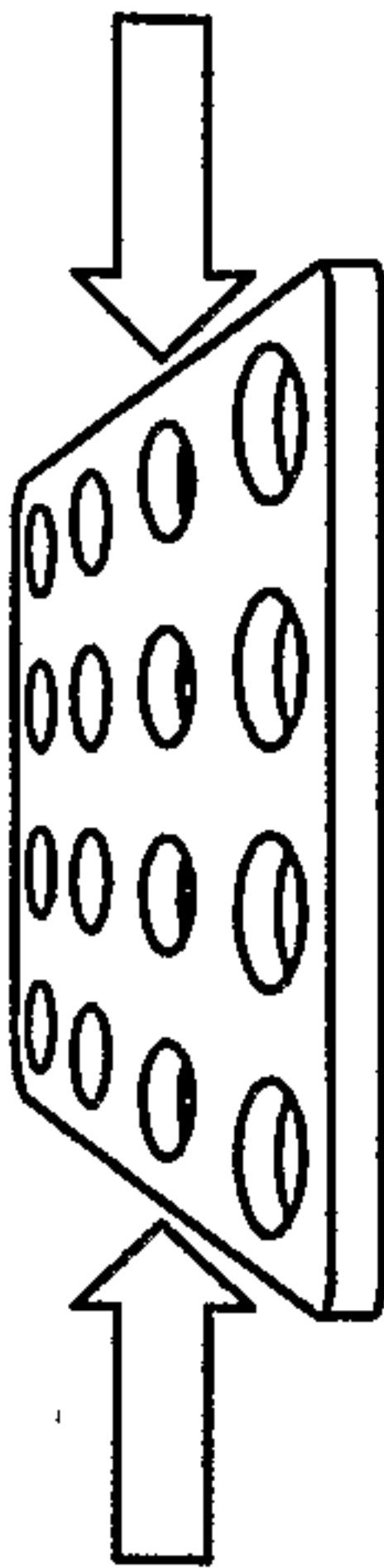
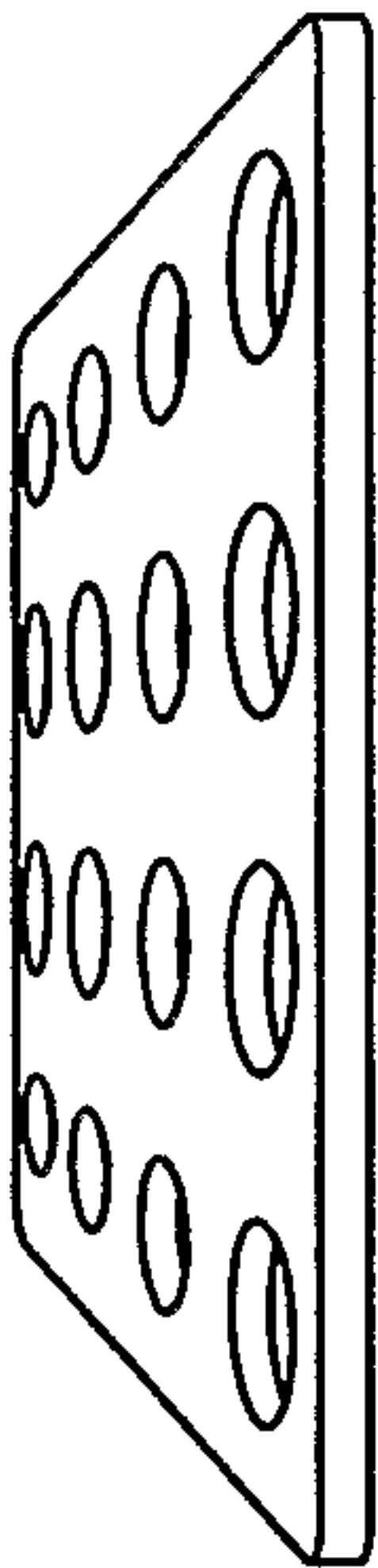


FIG. 3A

FIG. 3B

FIG. 3C

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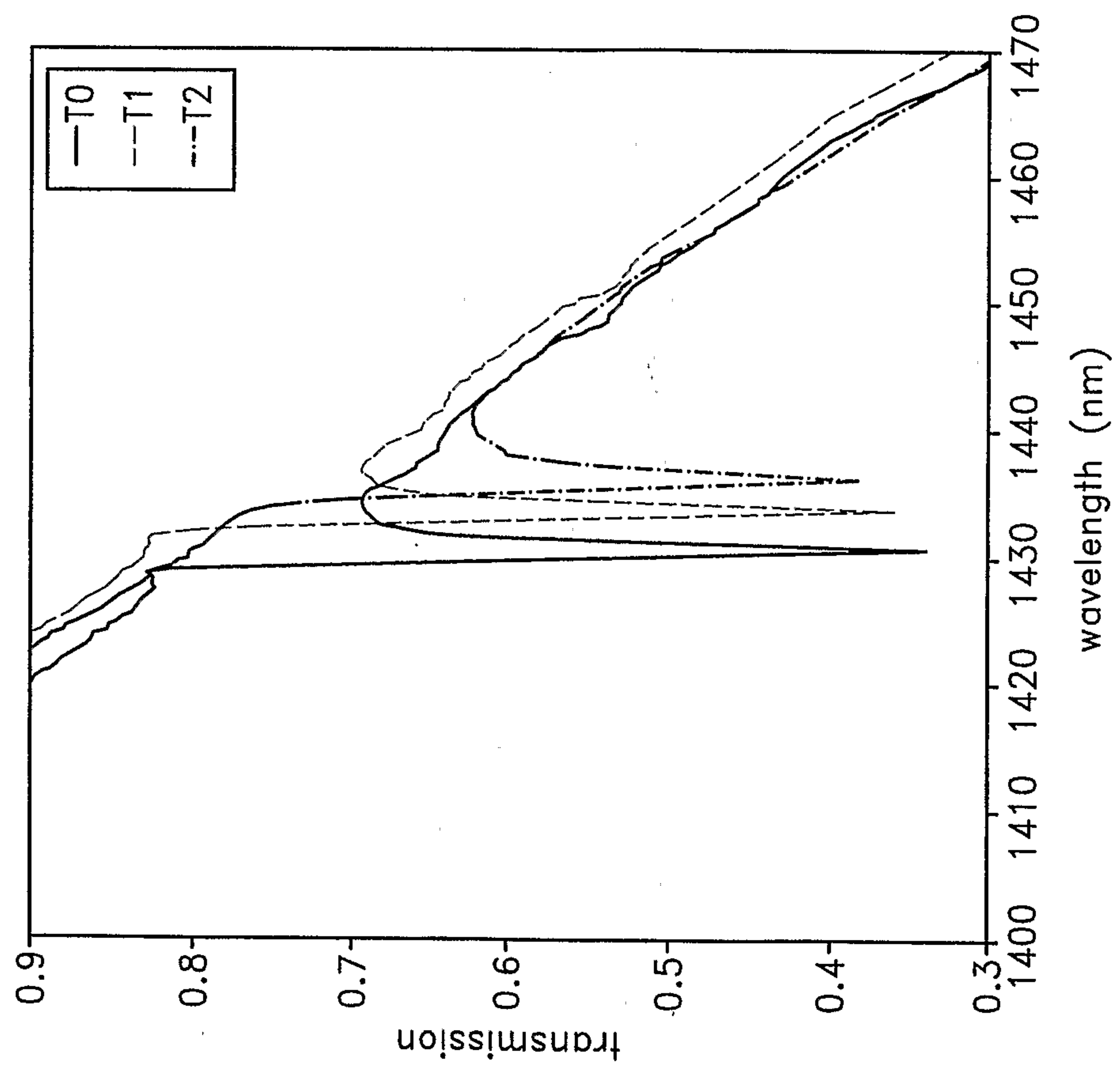


FIG. 4

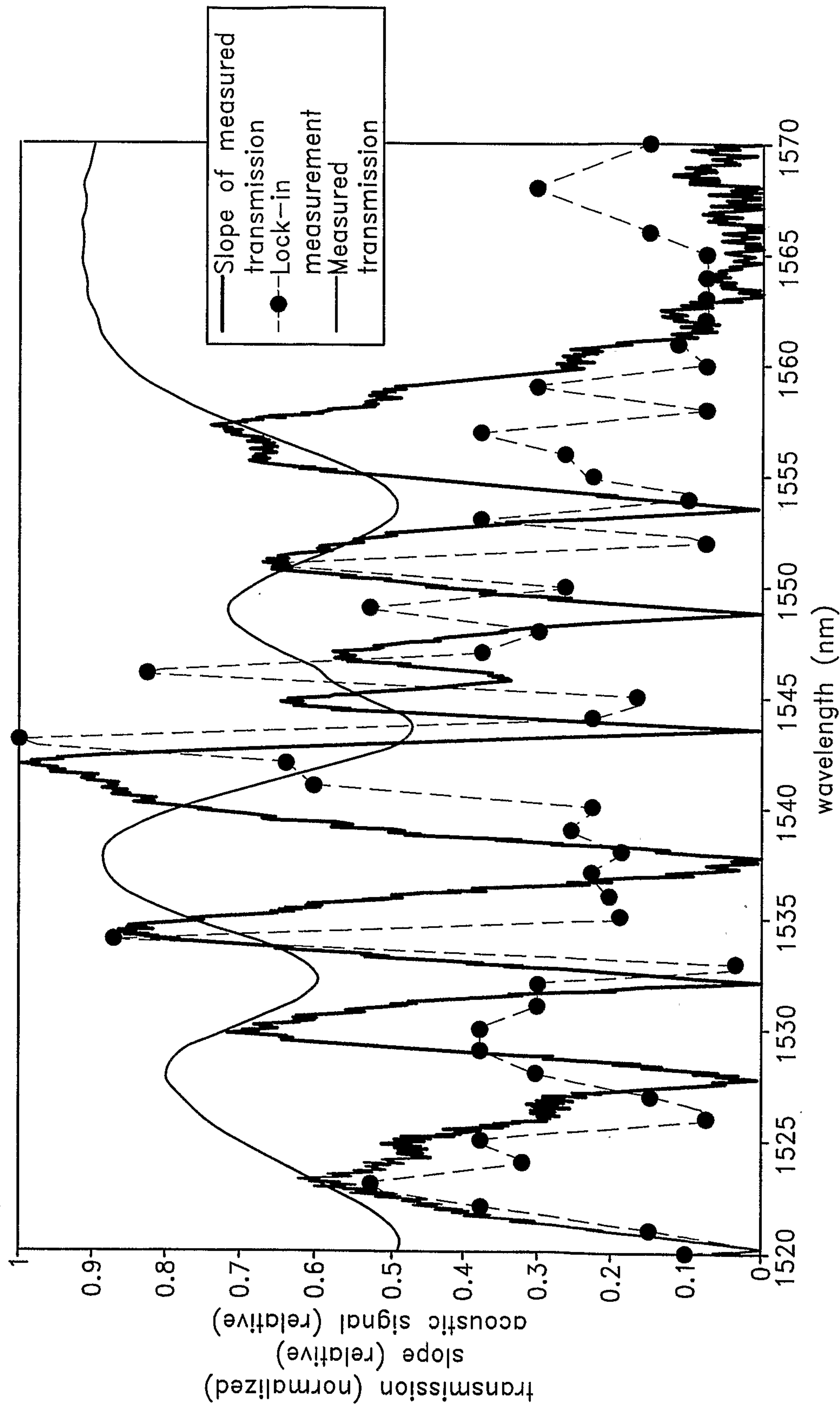


FIG. 5

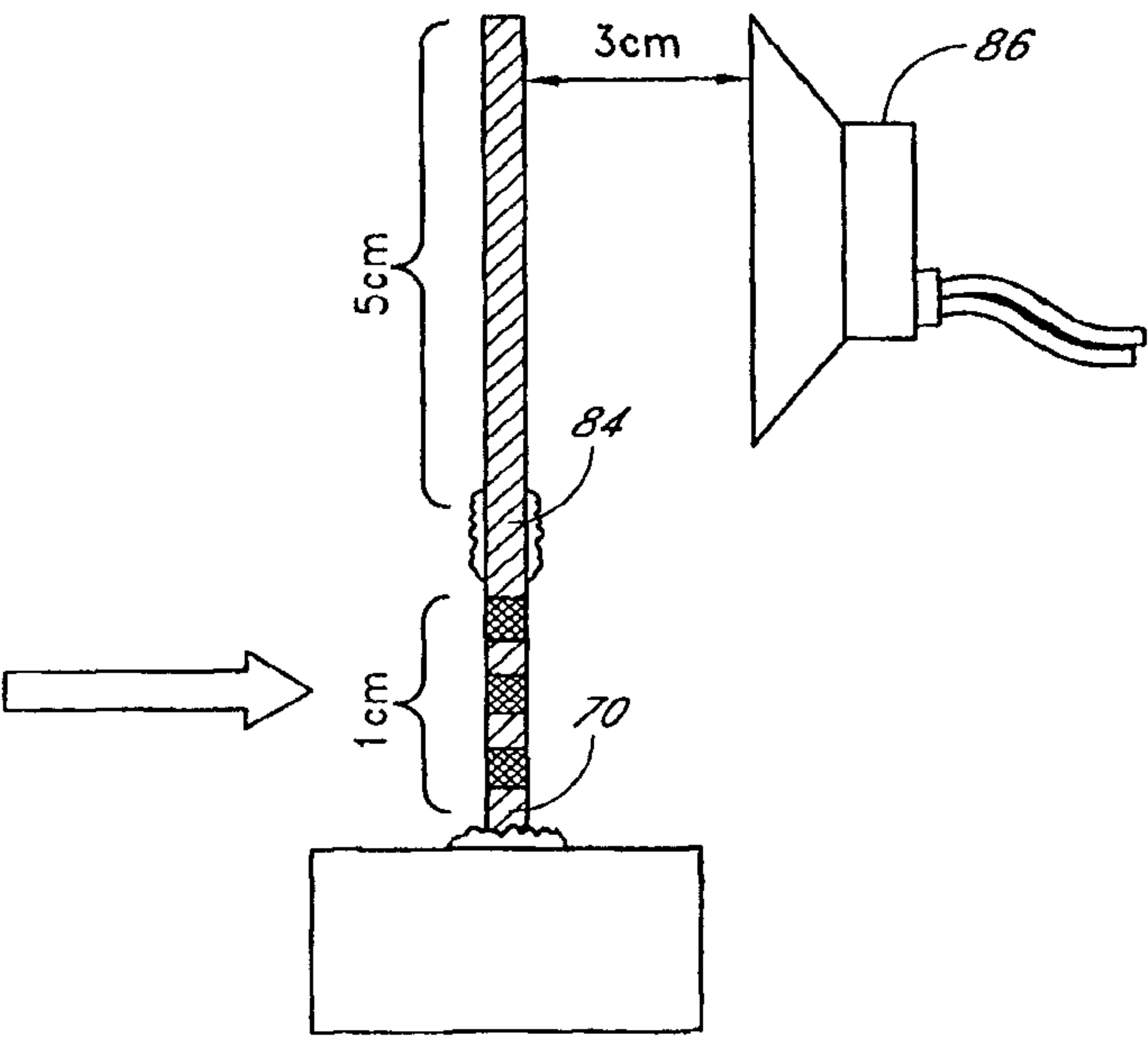


FIG. 6

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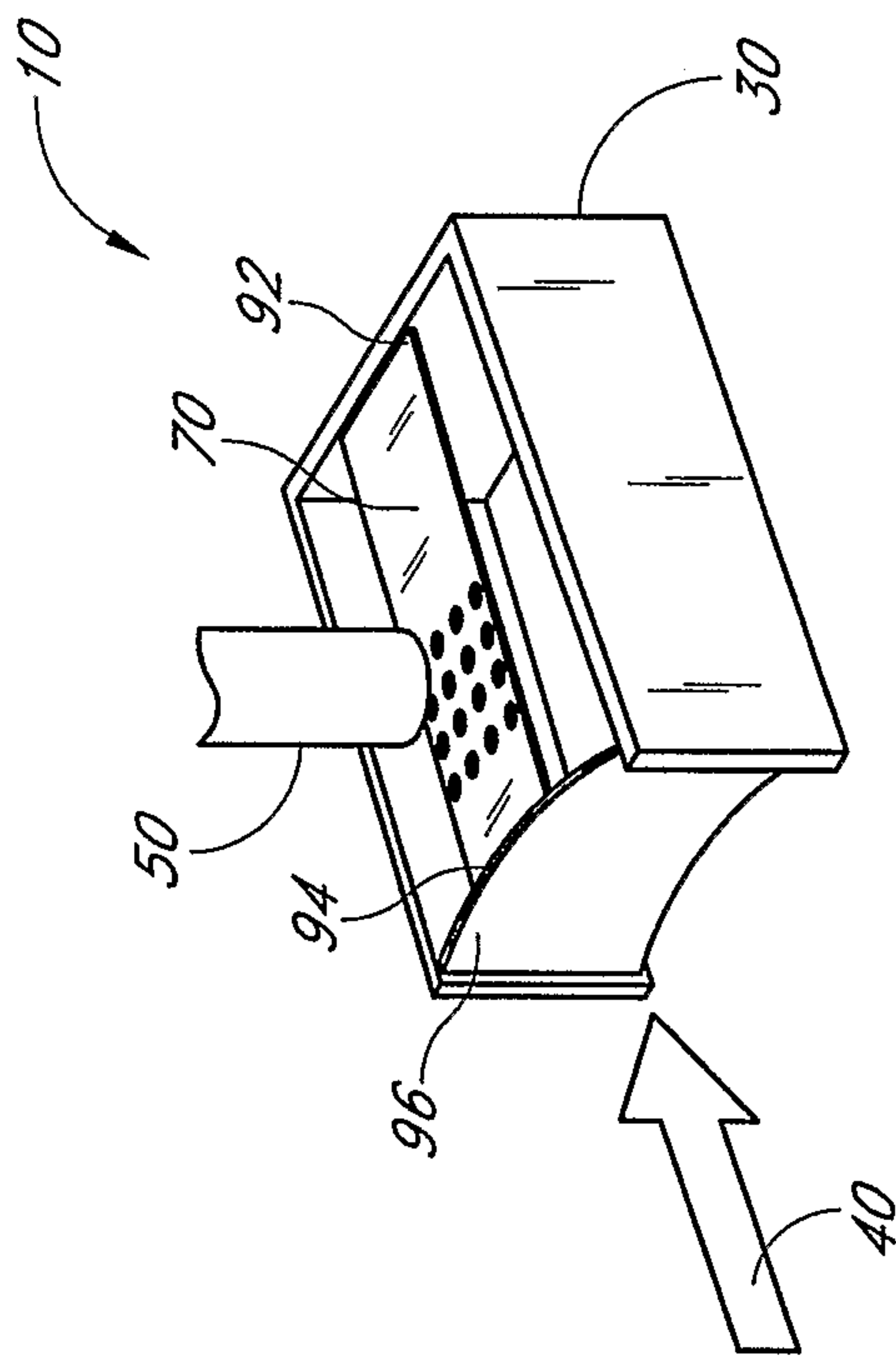


FIG. 7A

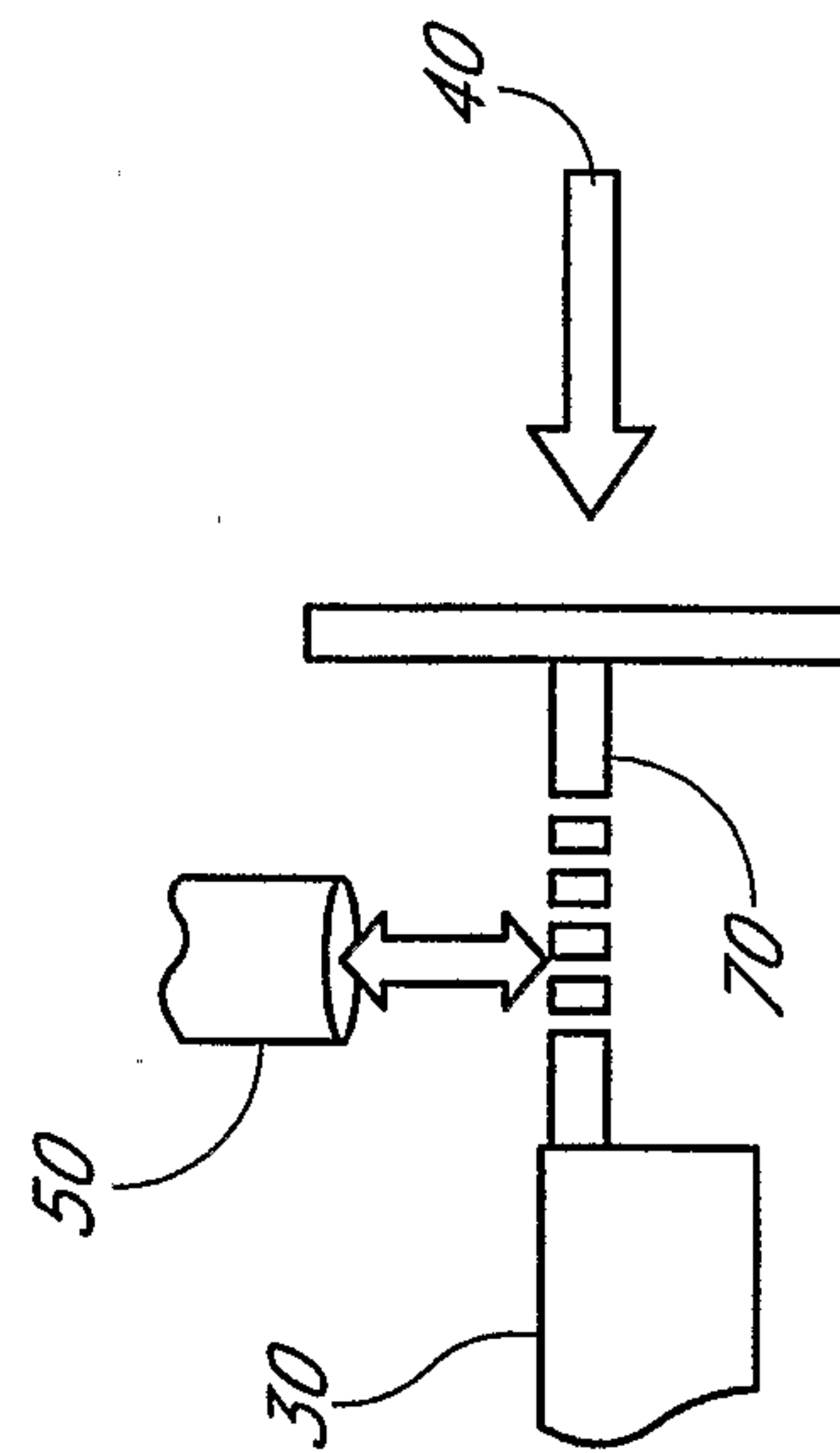


FIG. 7B

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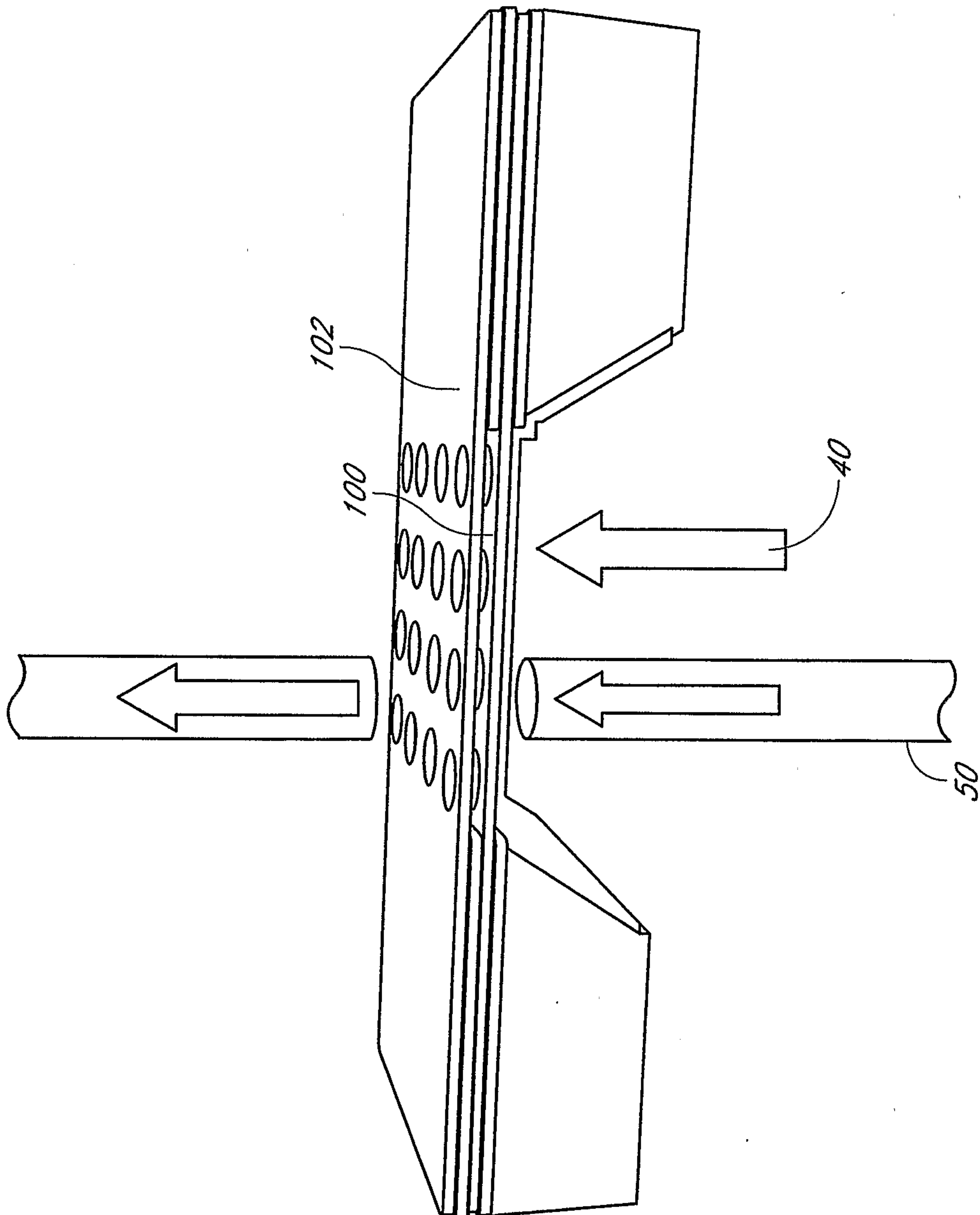
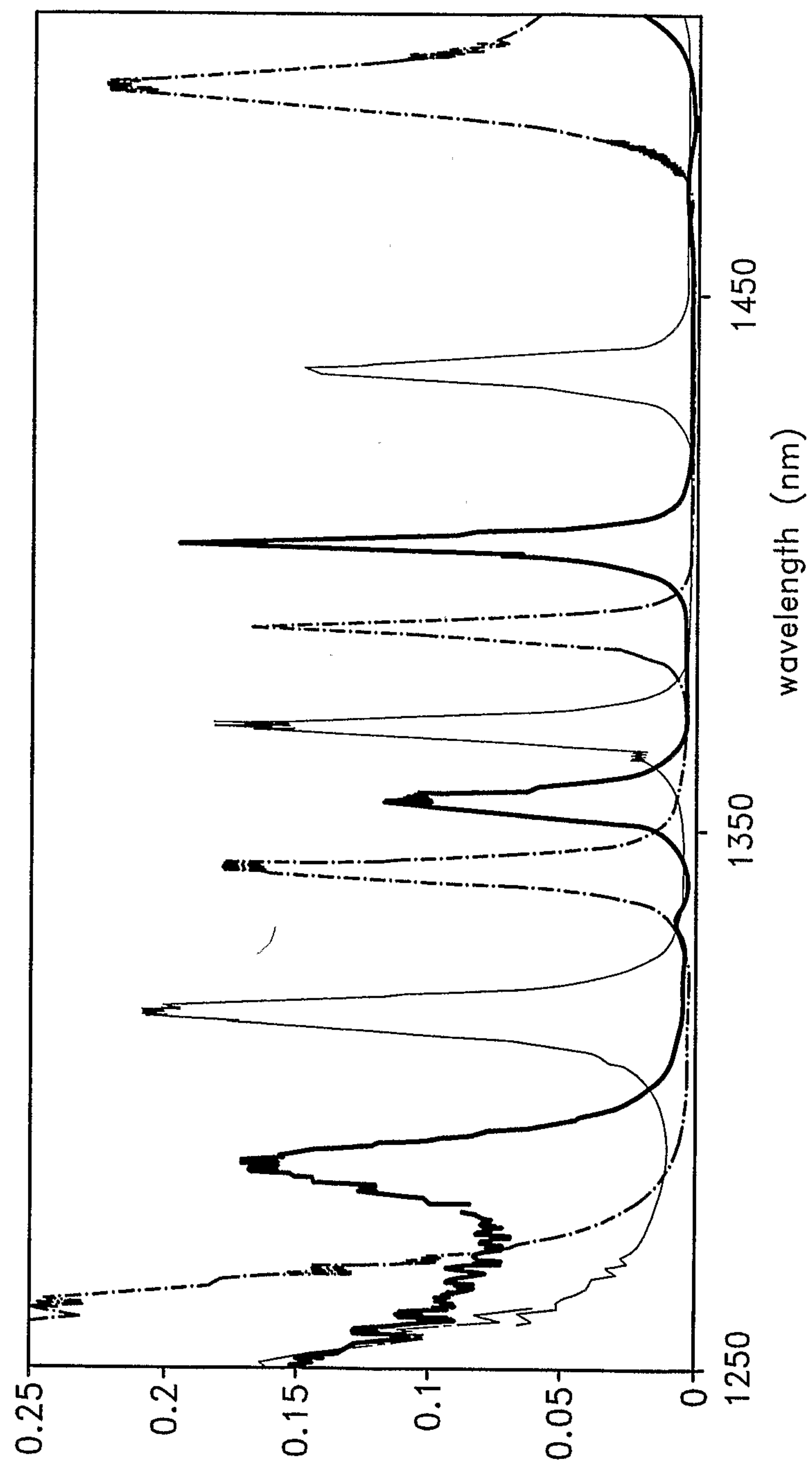
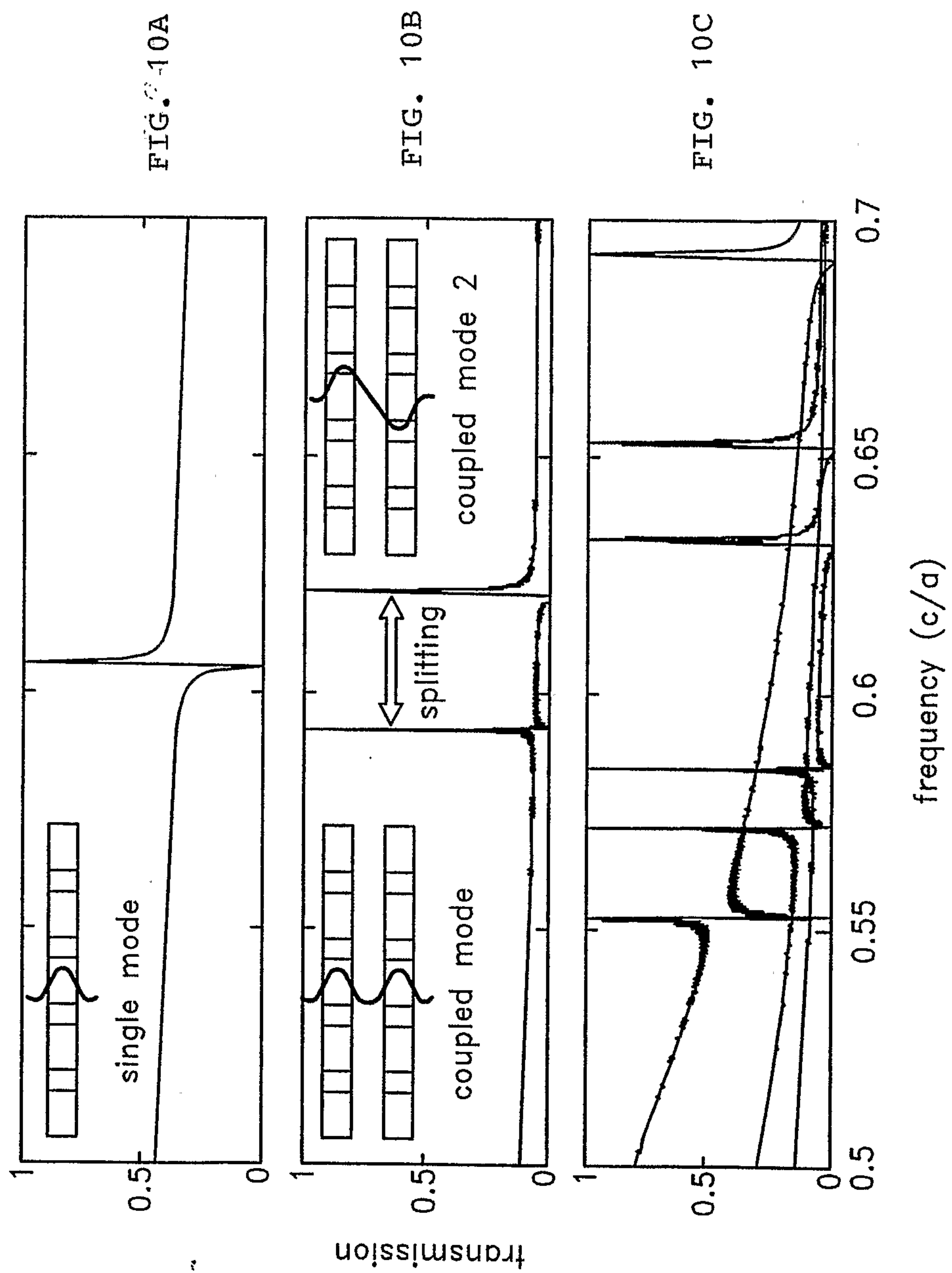


FIG. 8

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*FIG. 9*

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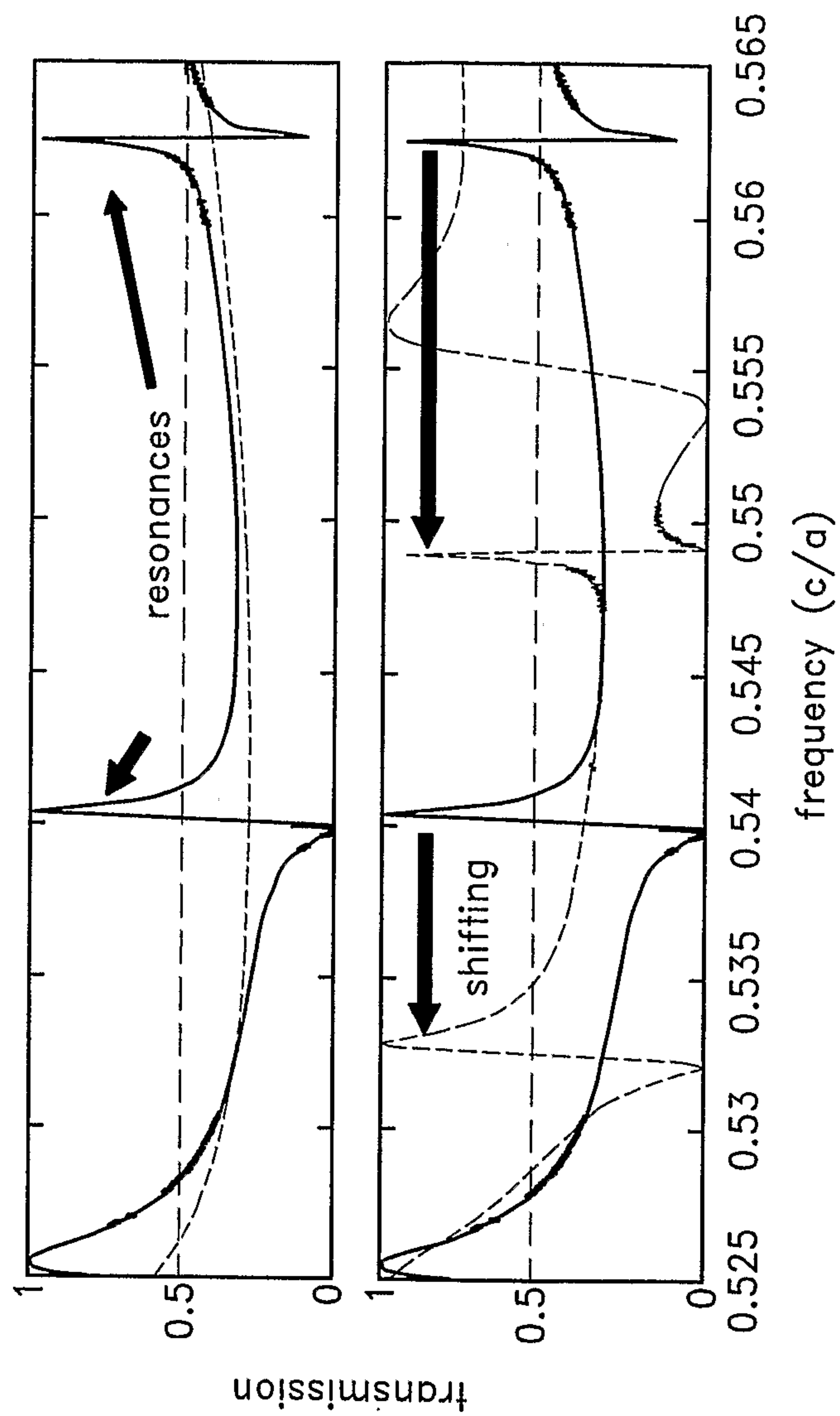


FIG. 11

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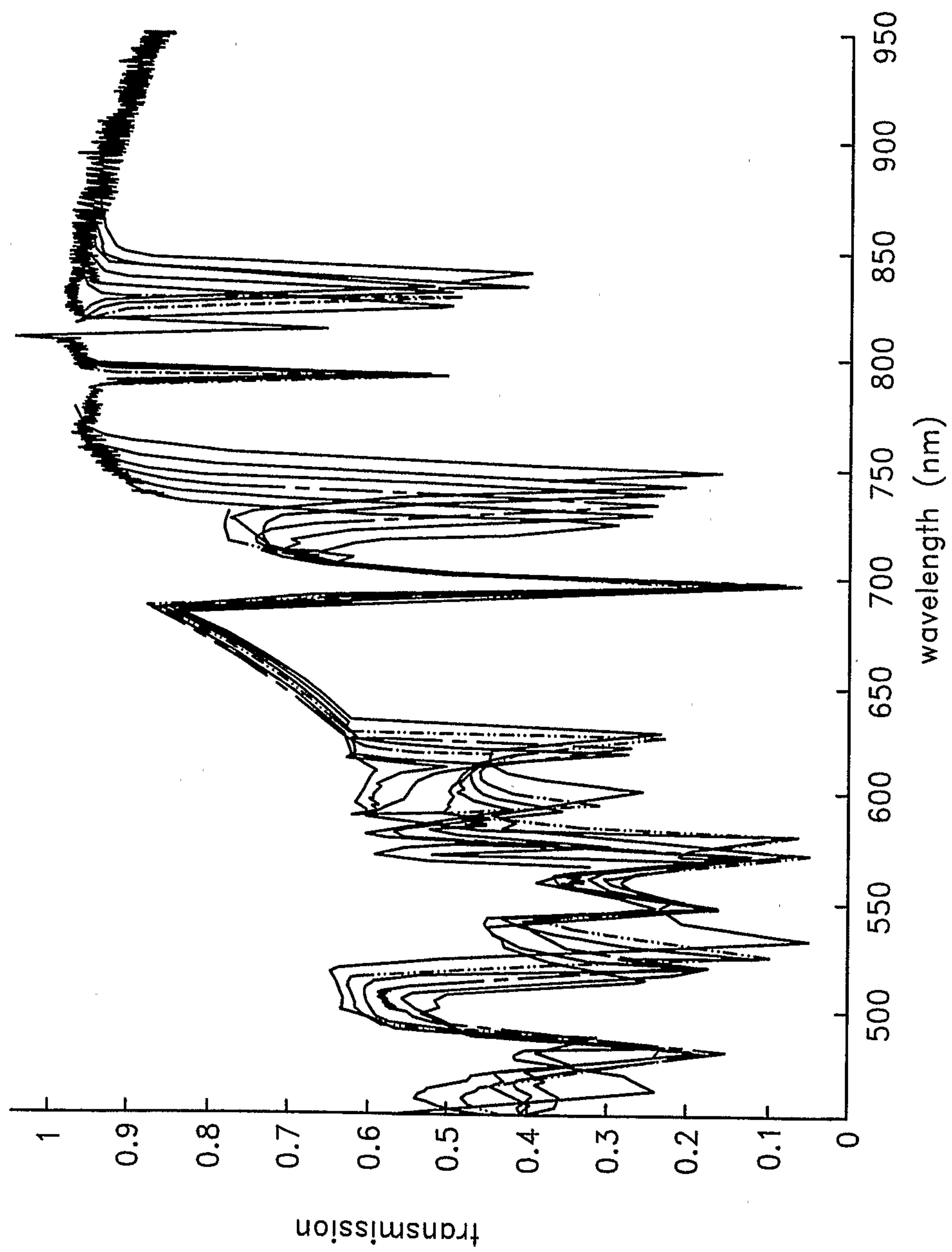
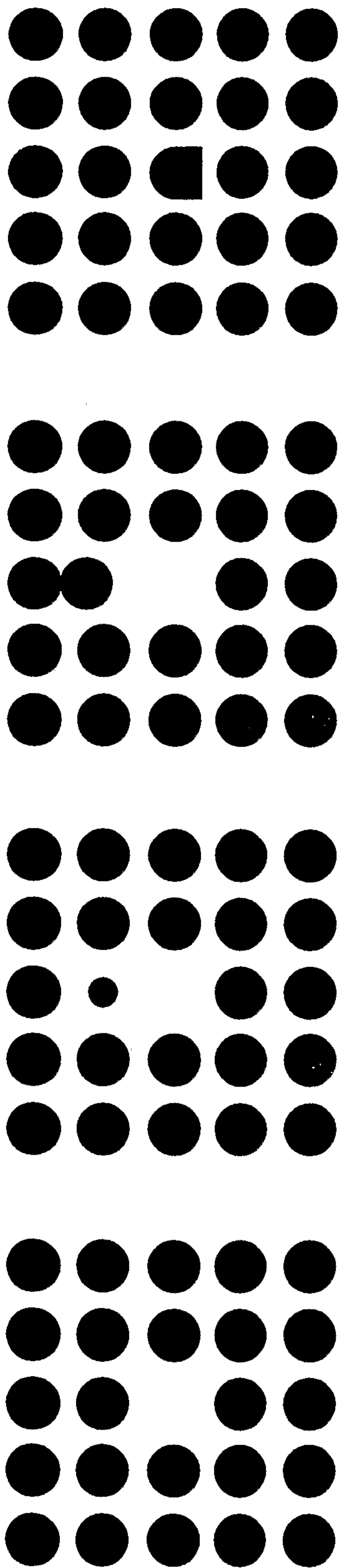
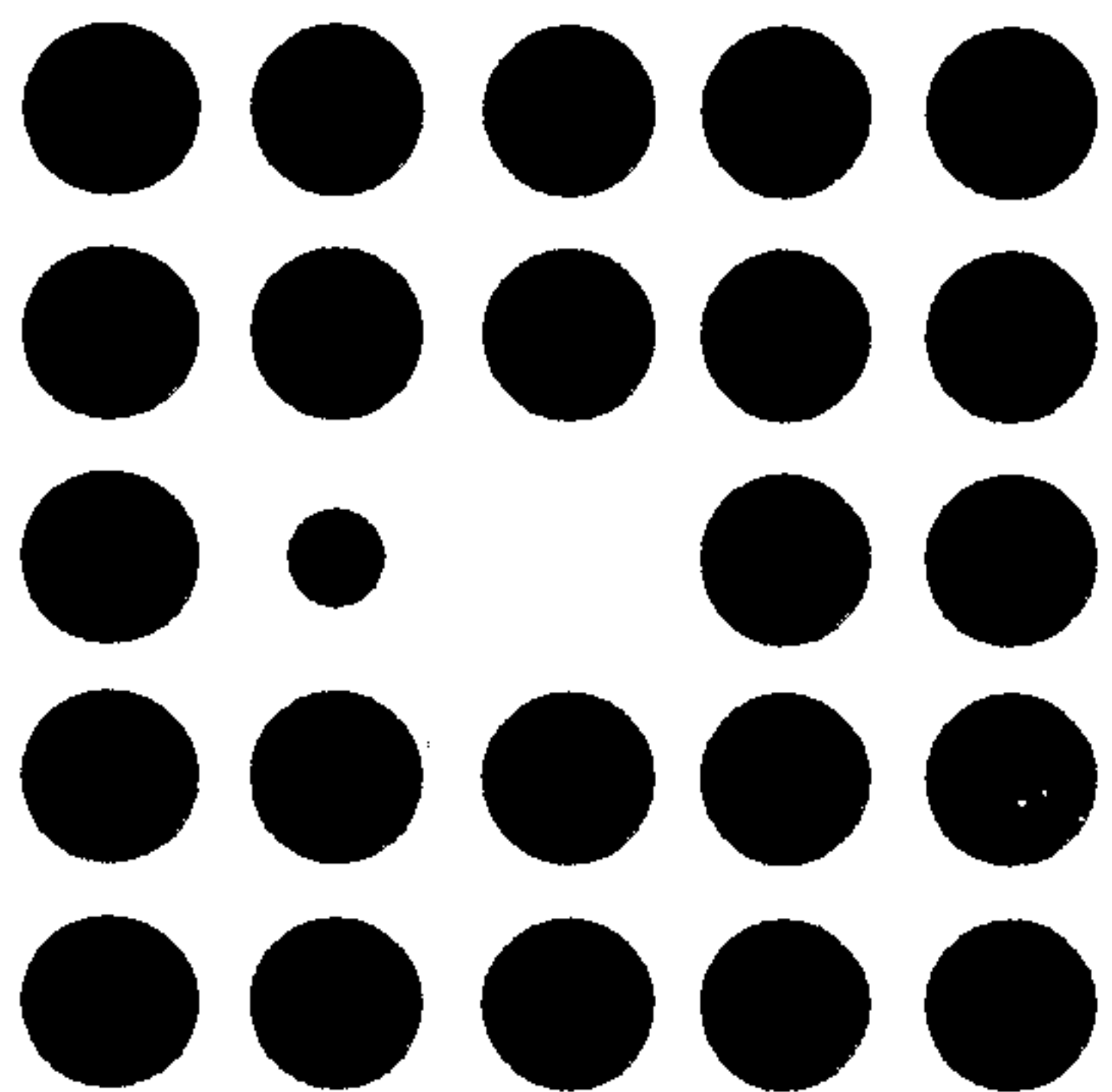
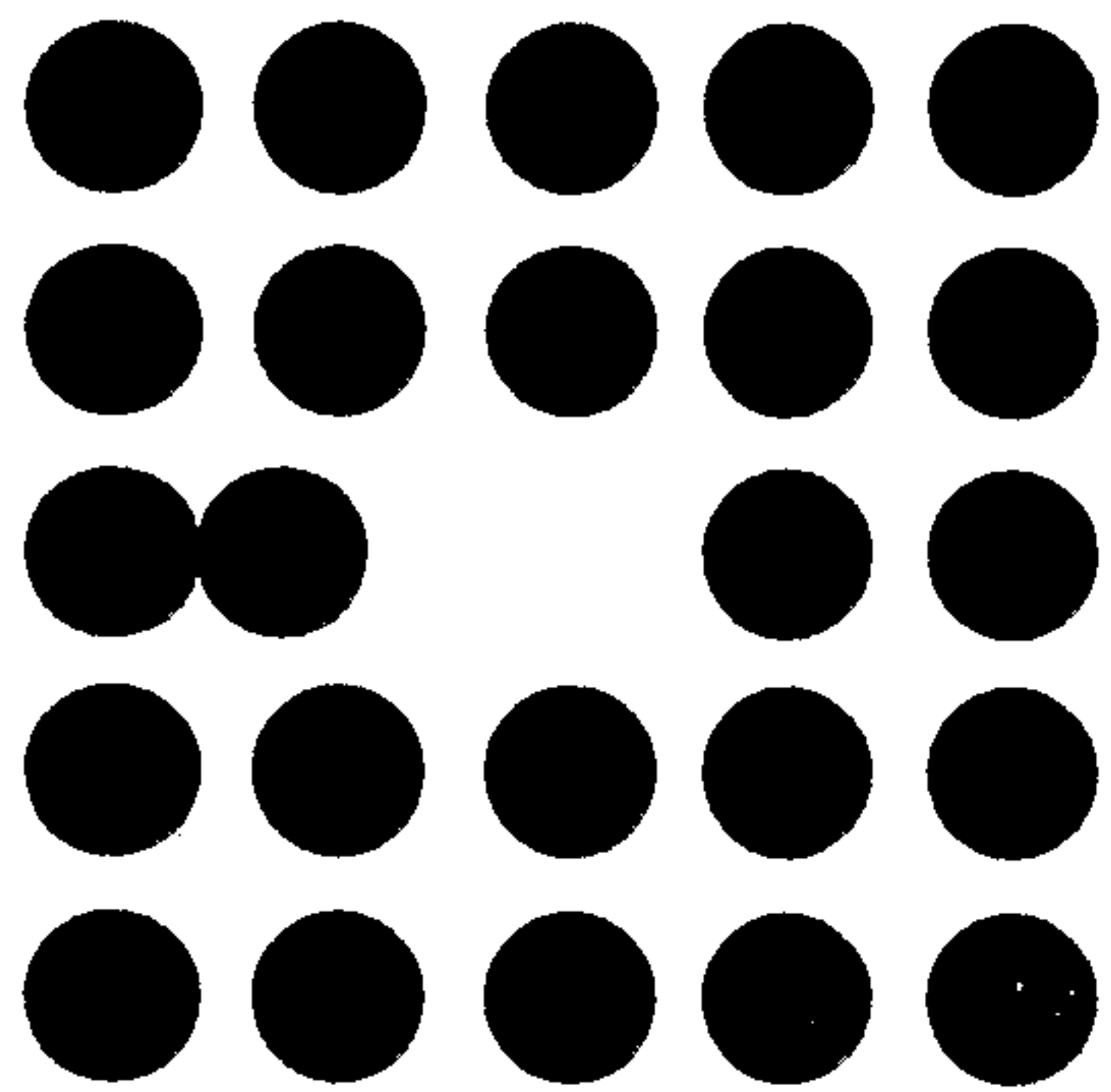
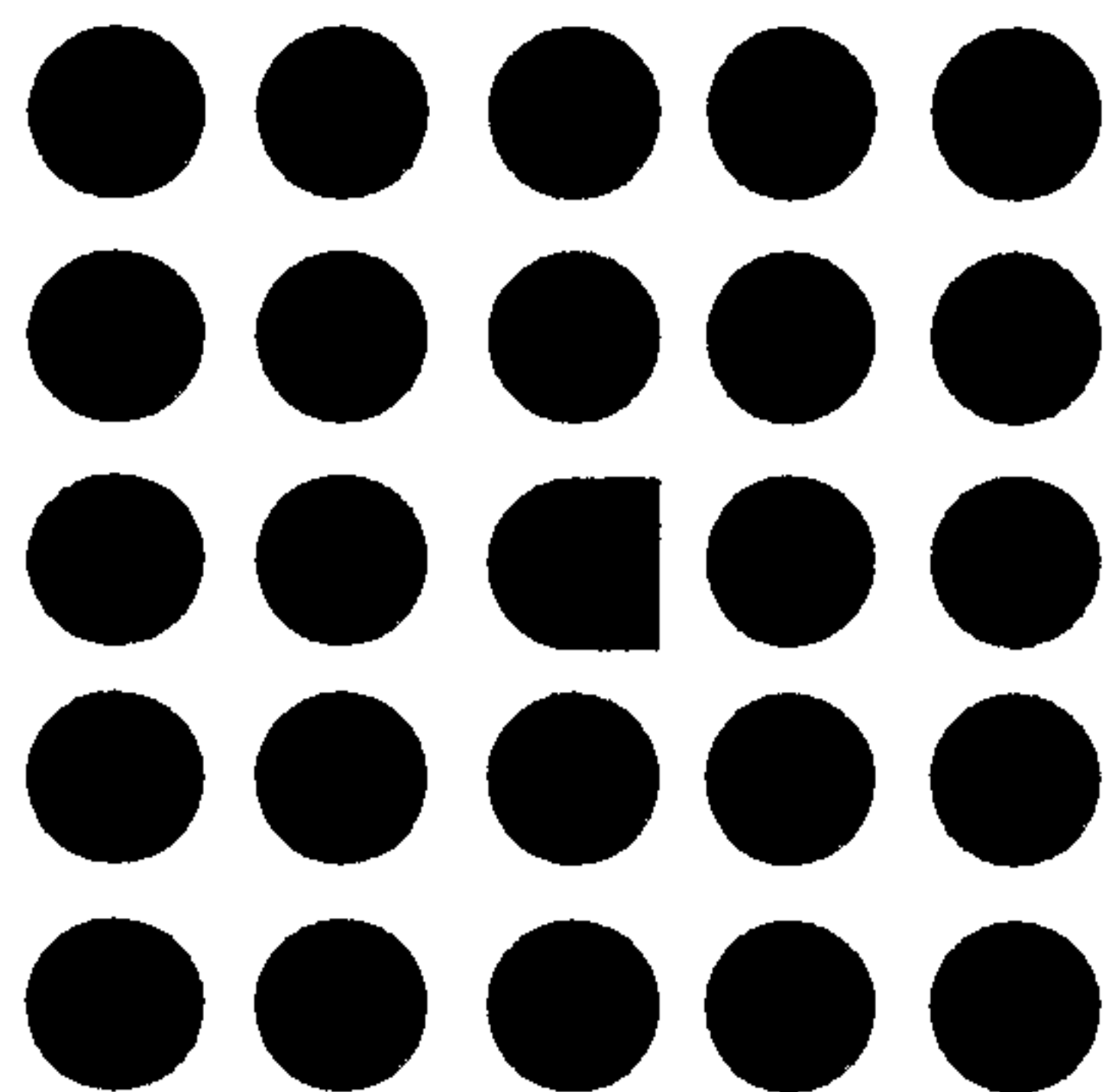
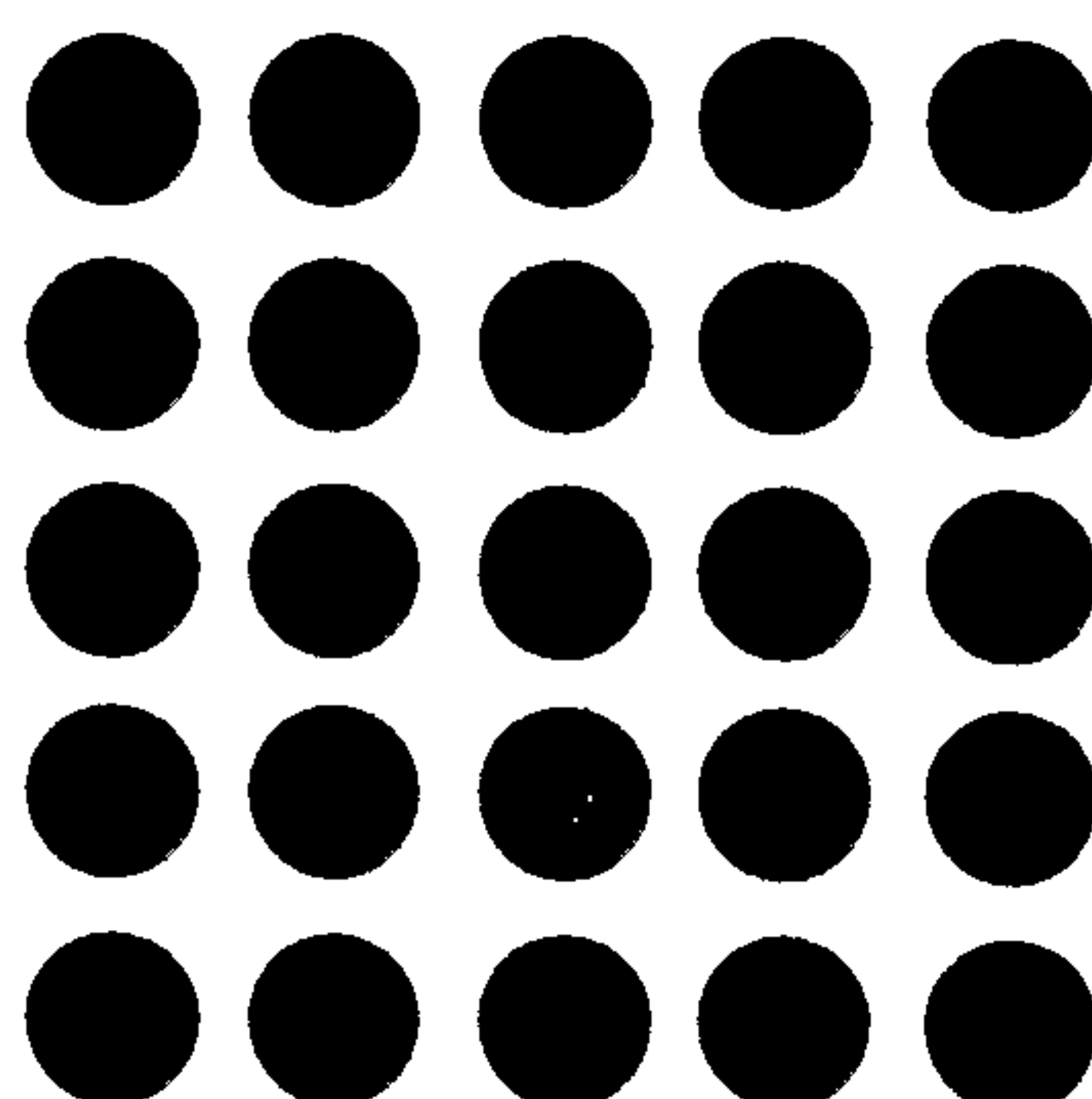
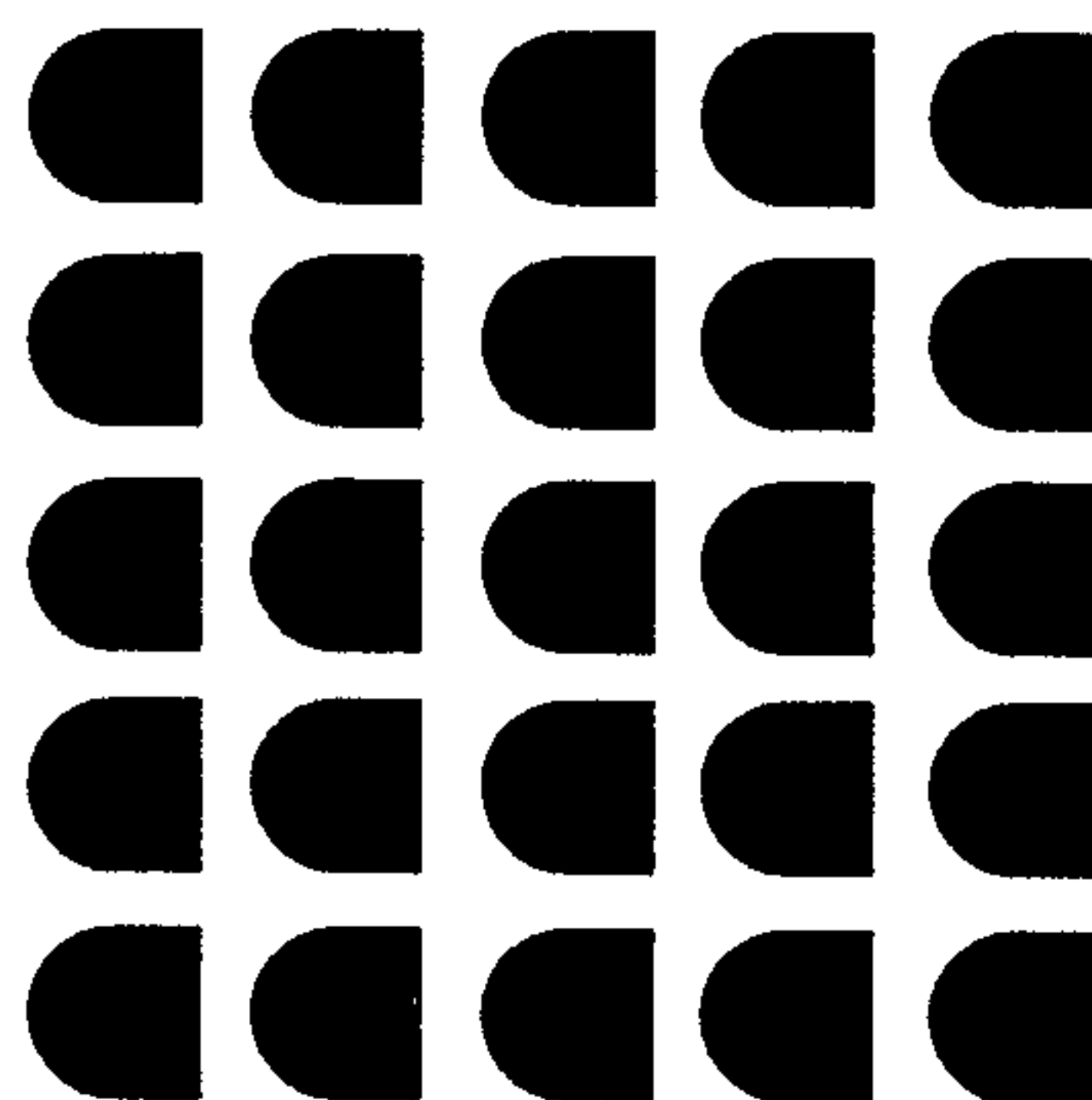


FIG. 12

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*FIG. 13A**FIG. 13B**FIG. 13C**FIG. 13D**FIG. 14A**FIG. 14B*

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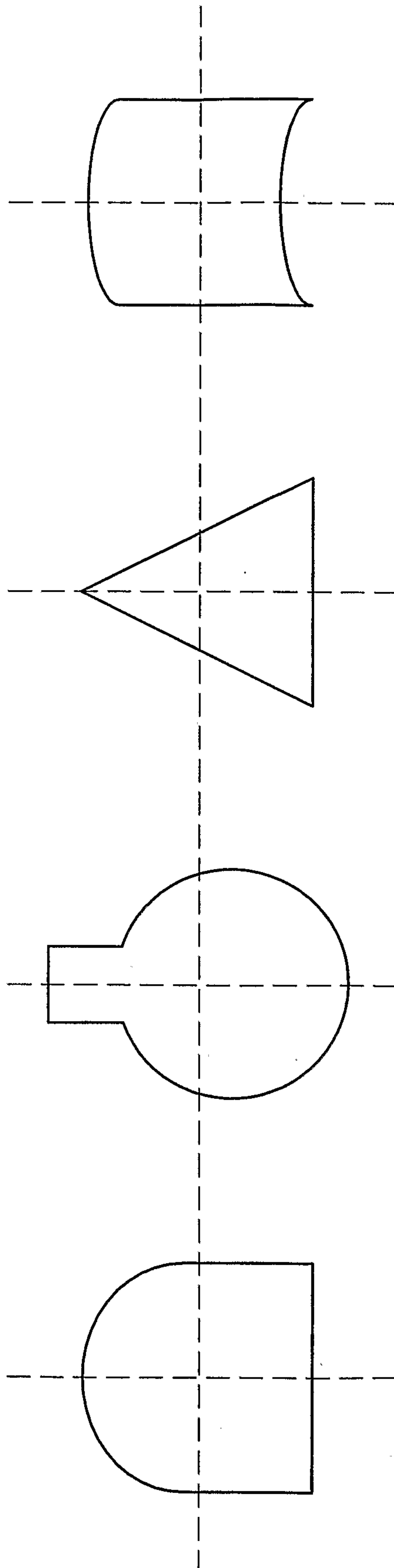
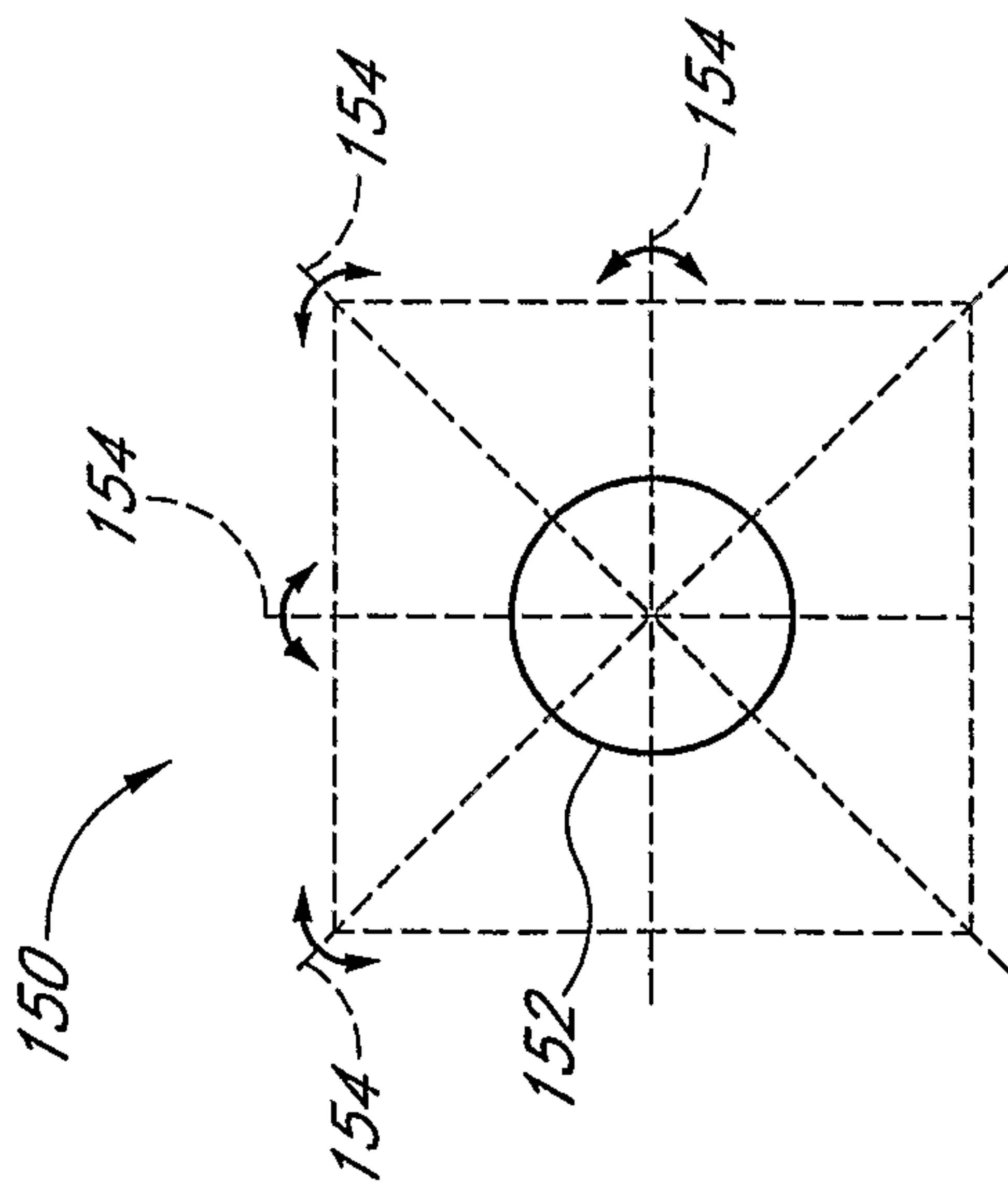
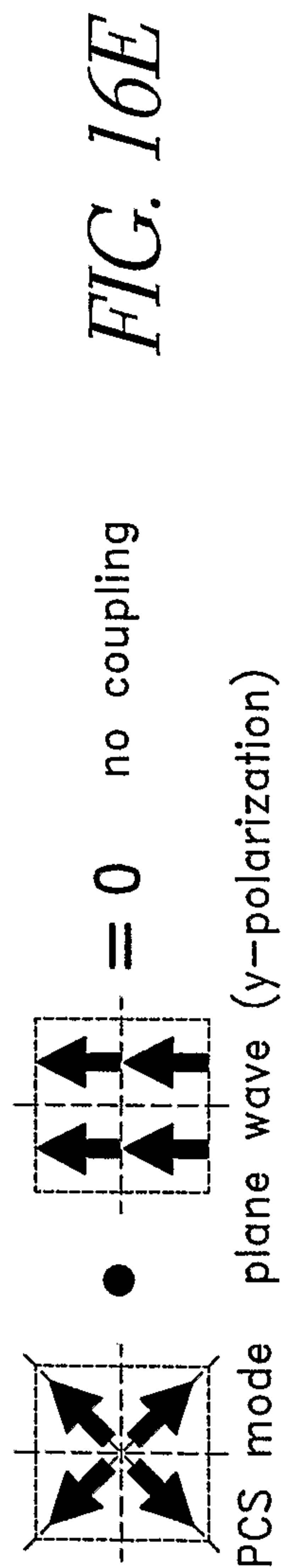
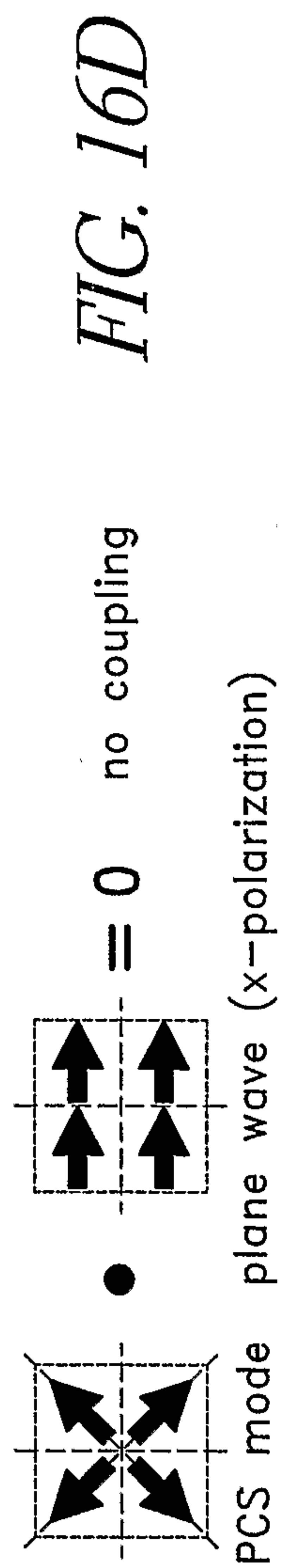
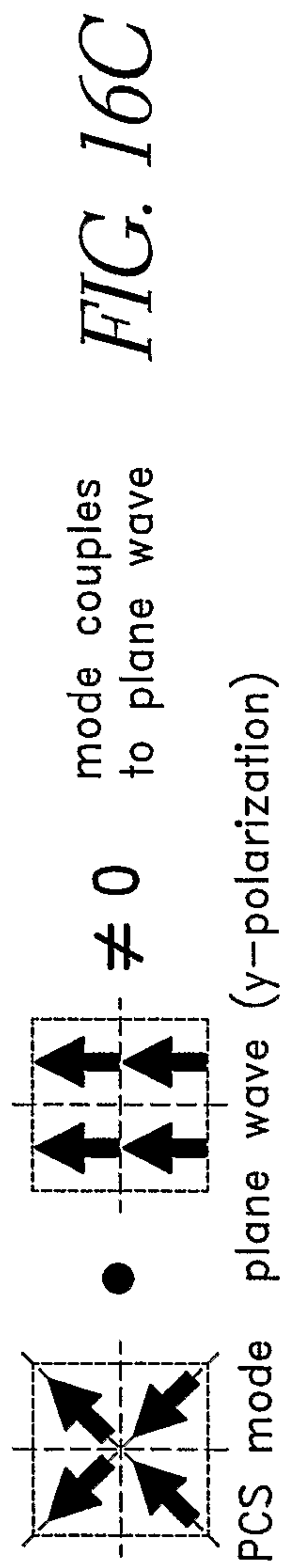
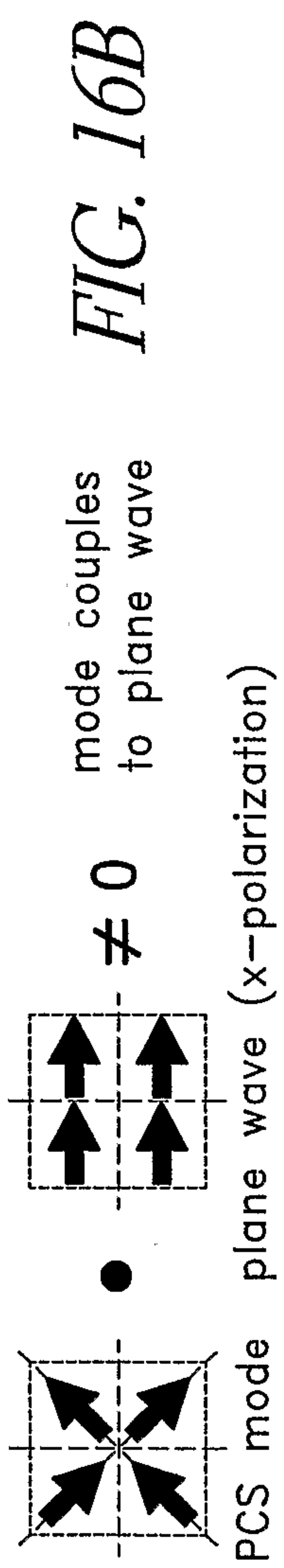


FIG. 15



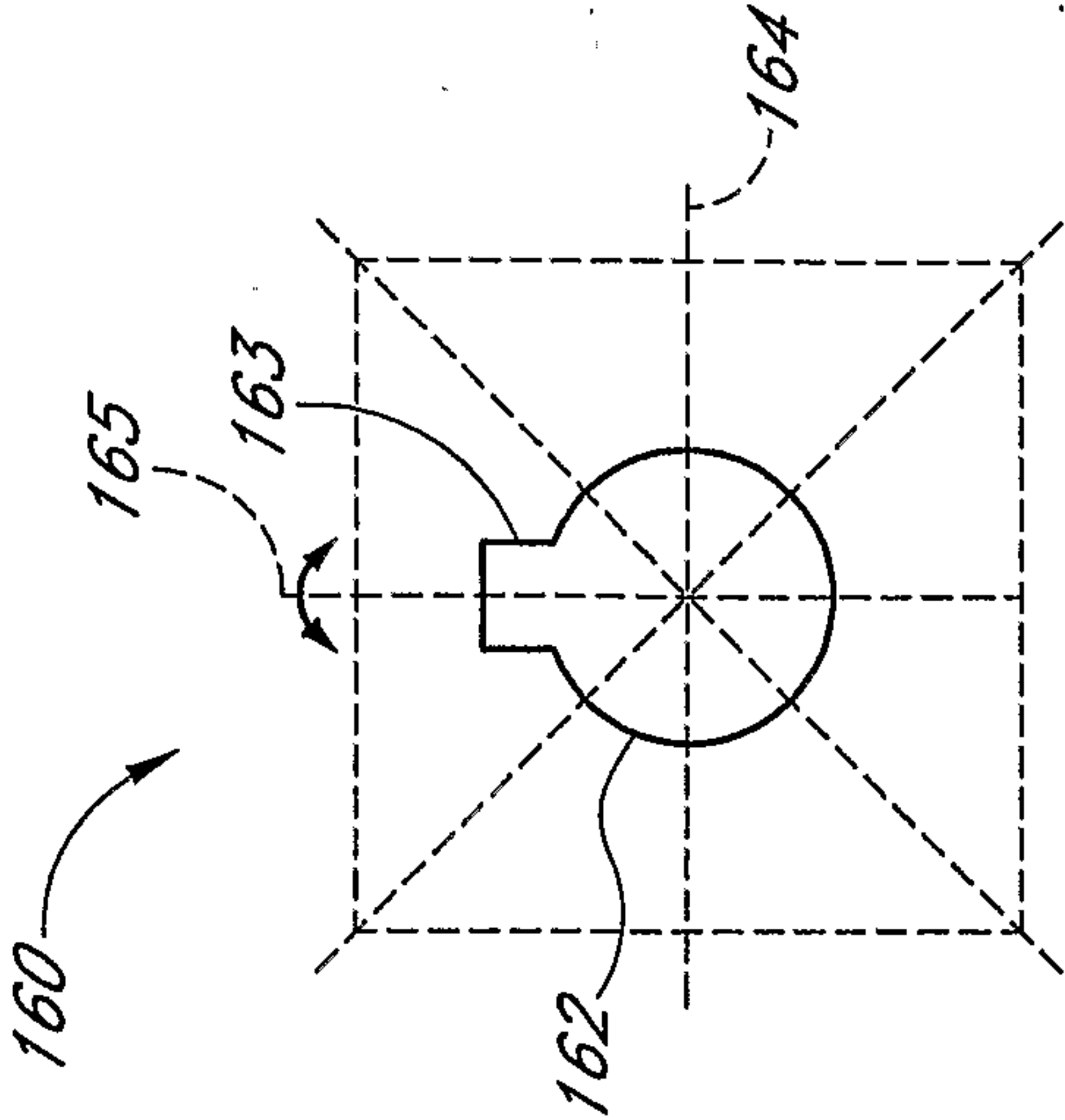


FIG. 17A



FIG. 17B

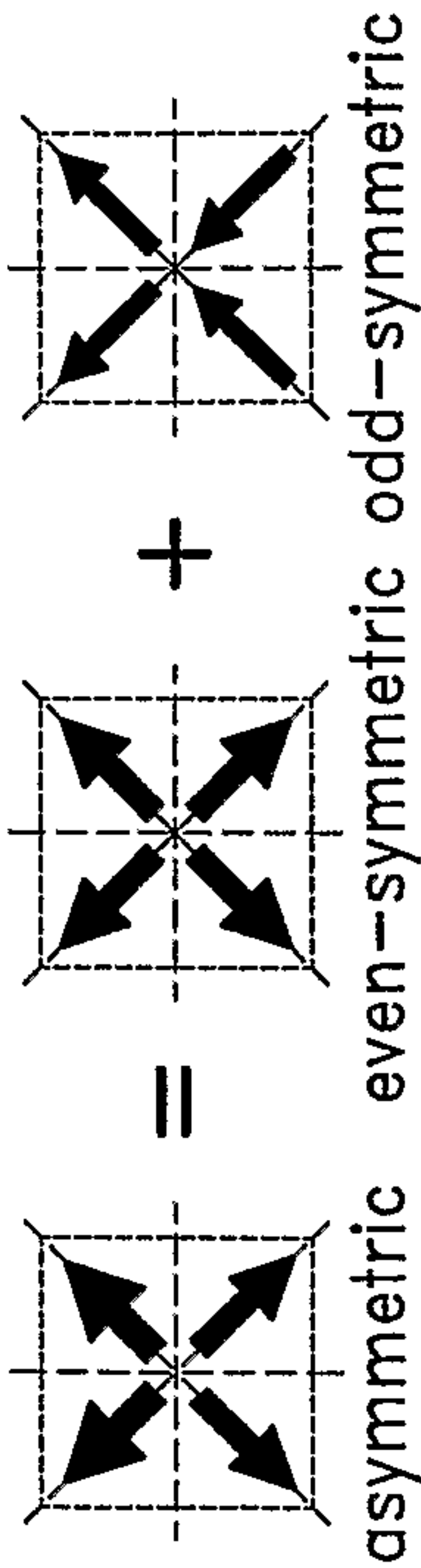


FIG. 17C

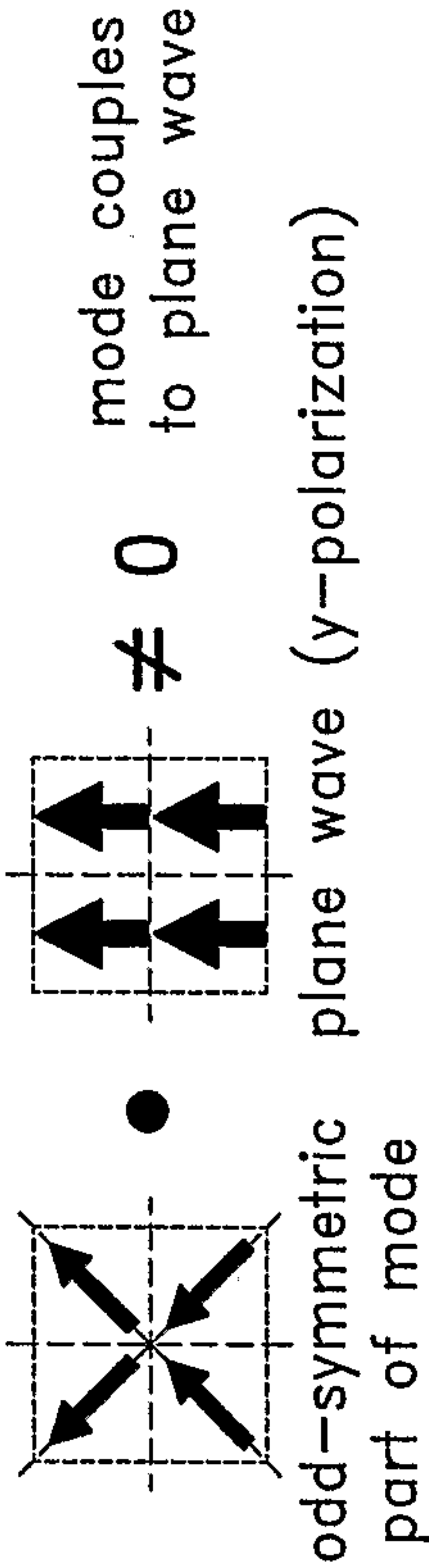


FIG. 17D

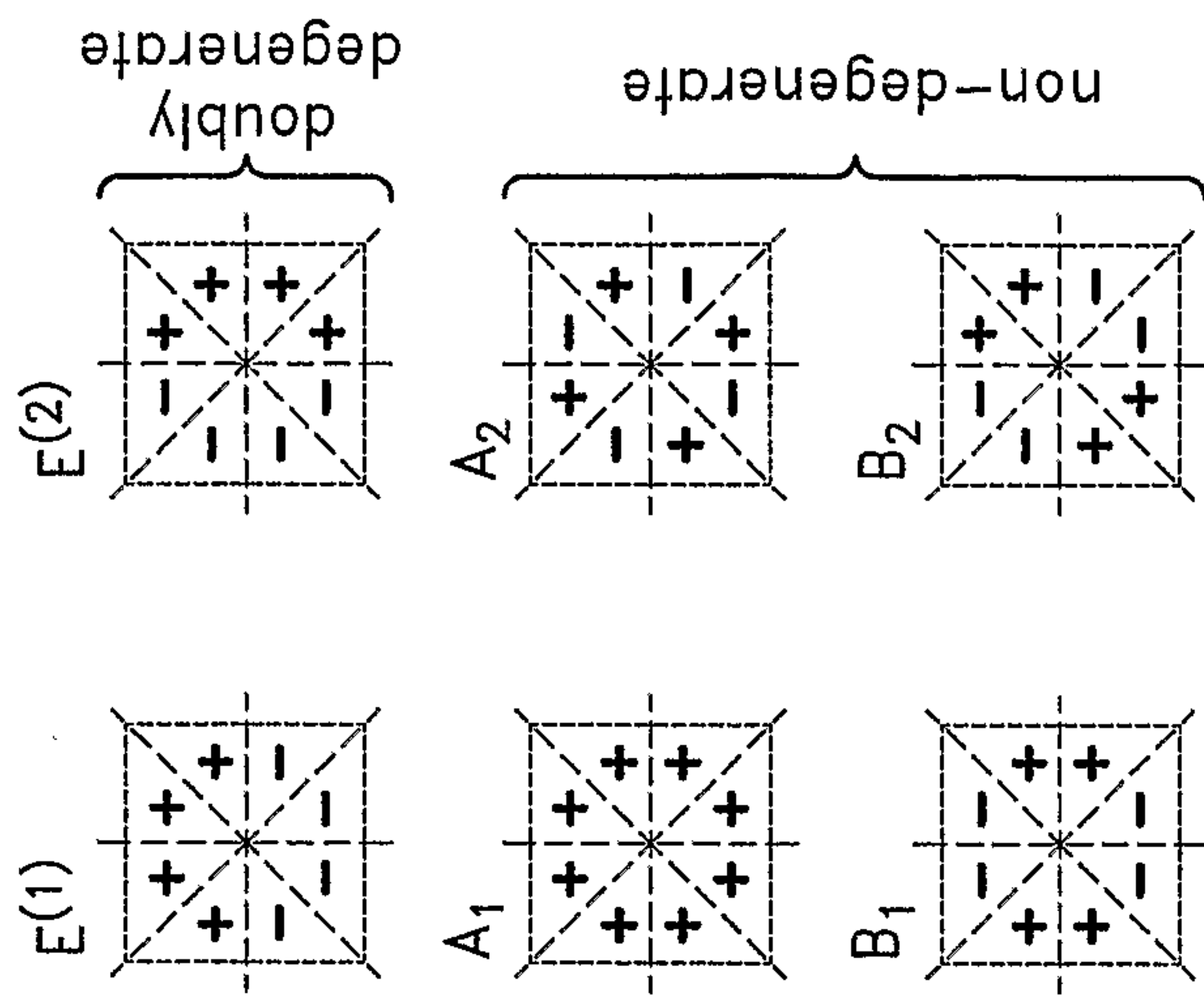


FIG. 18B

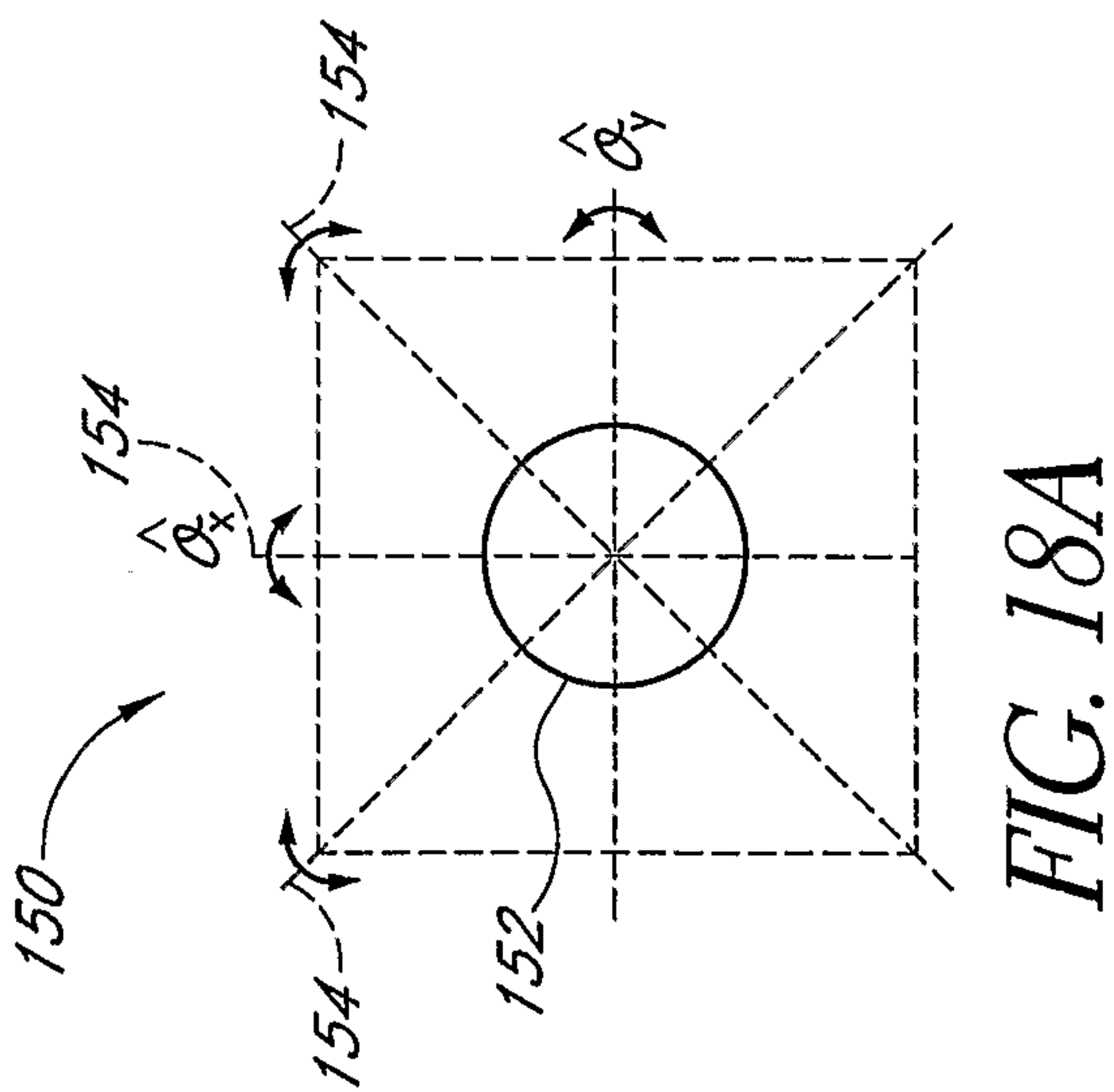


FIG. 18A

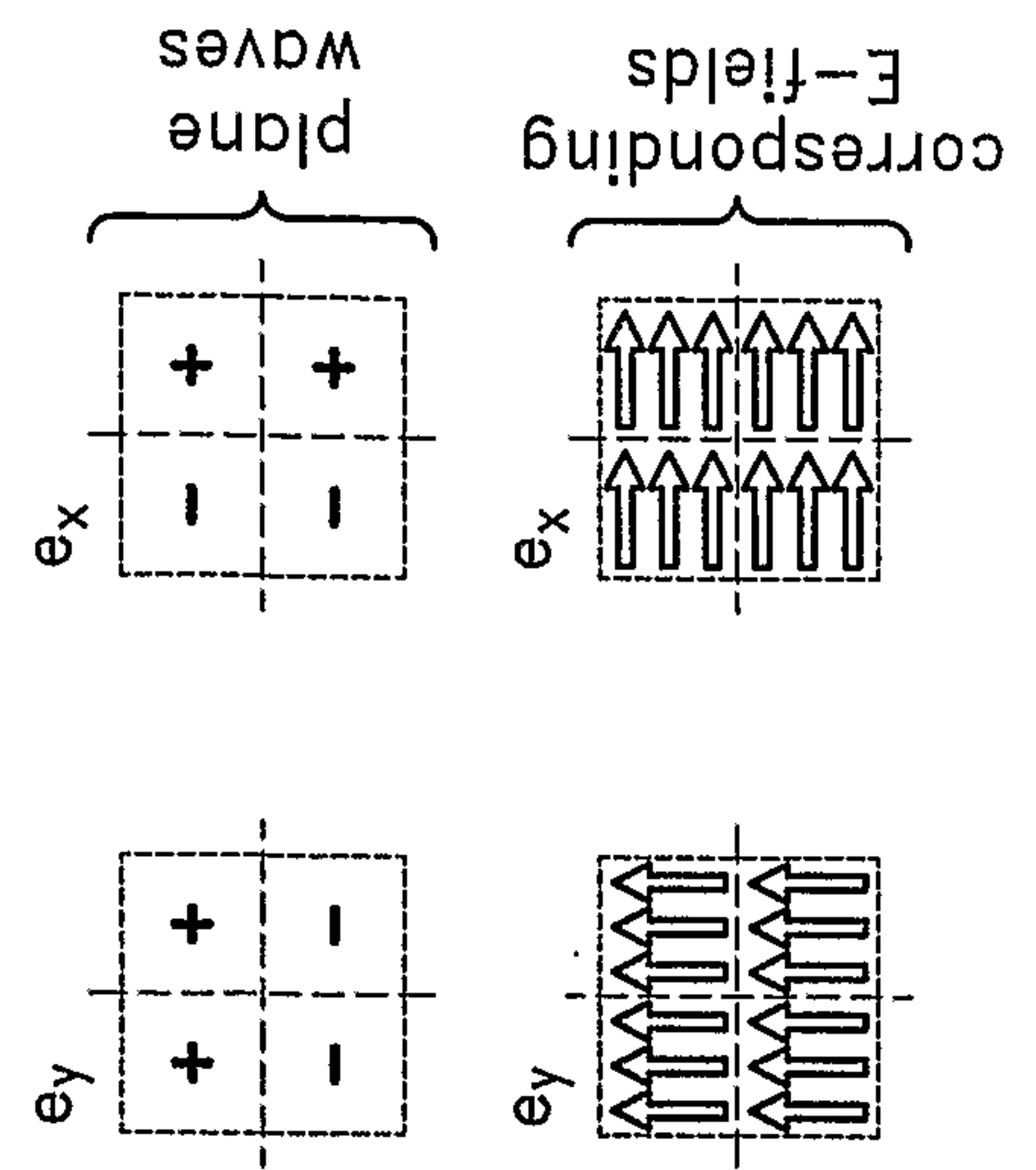


FIG. 18C

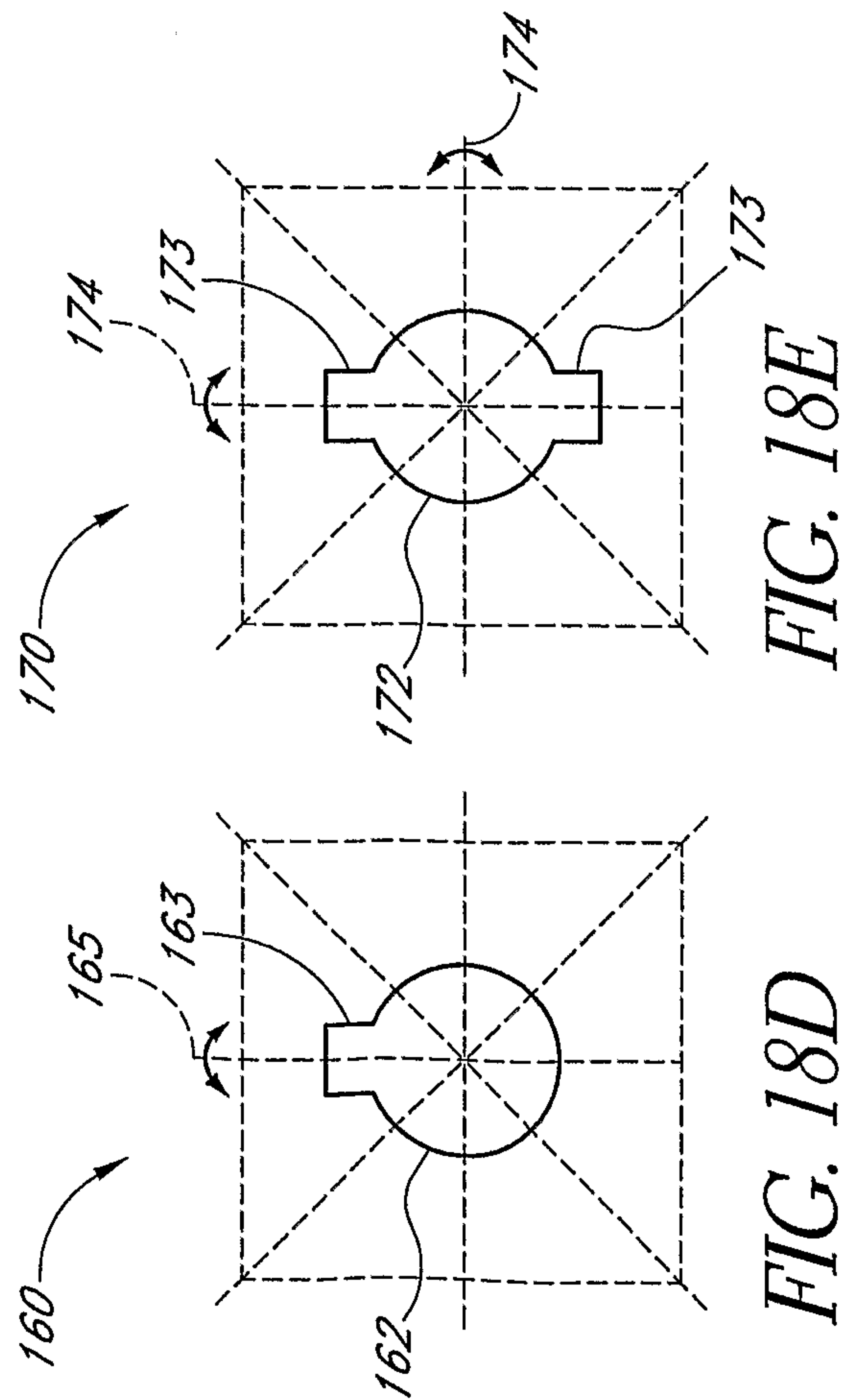


FIG. 18D

FIG. 18E

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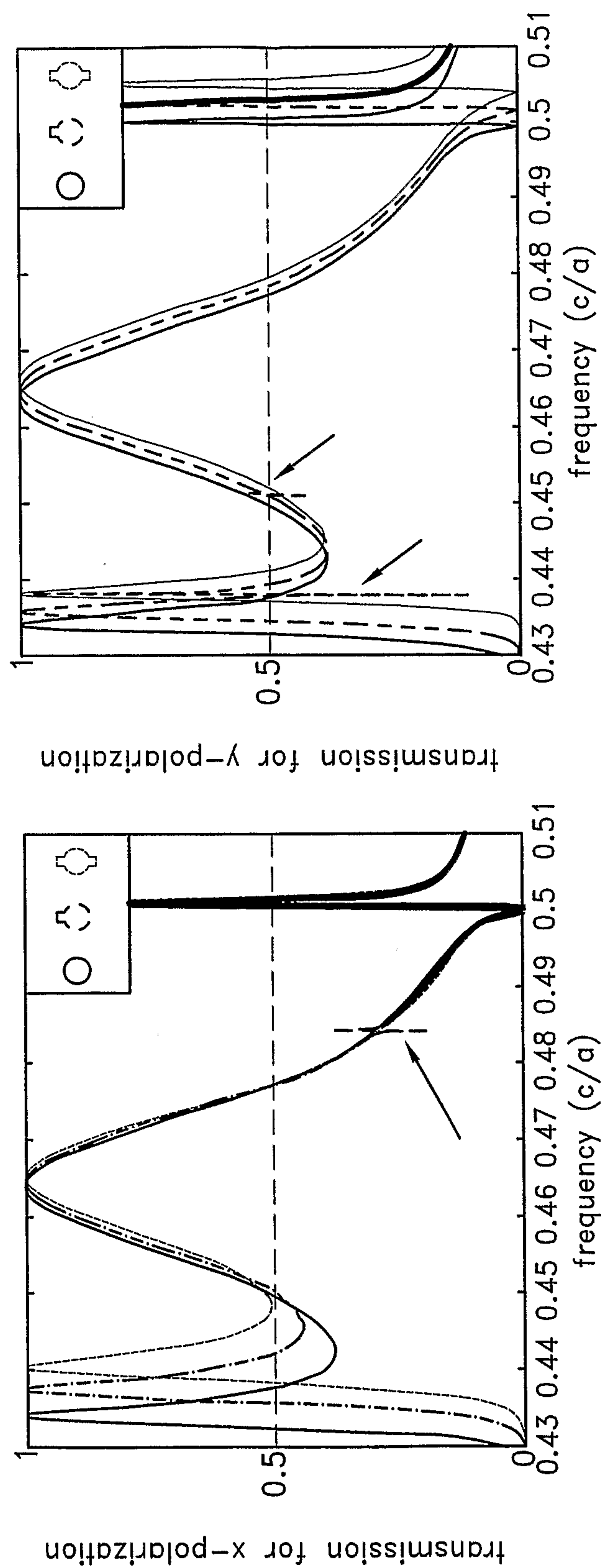


FIG. 19B

FIG. 19A

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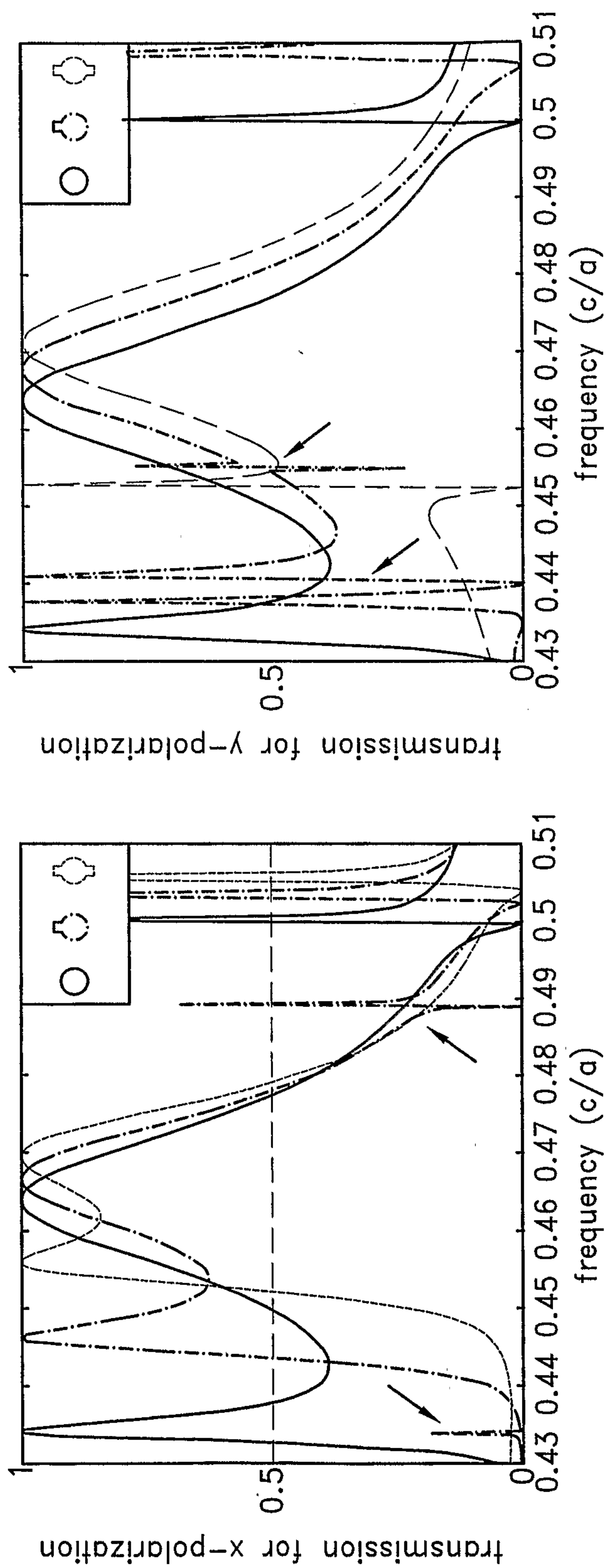
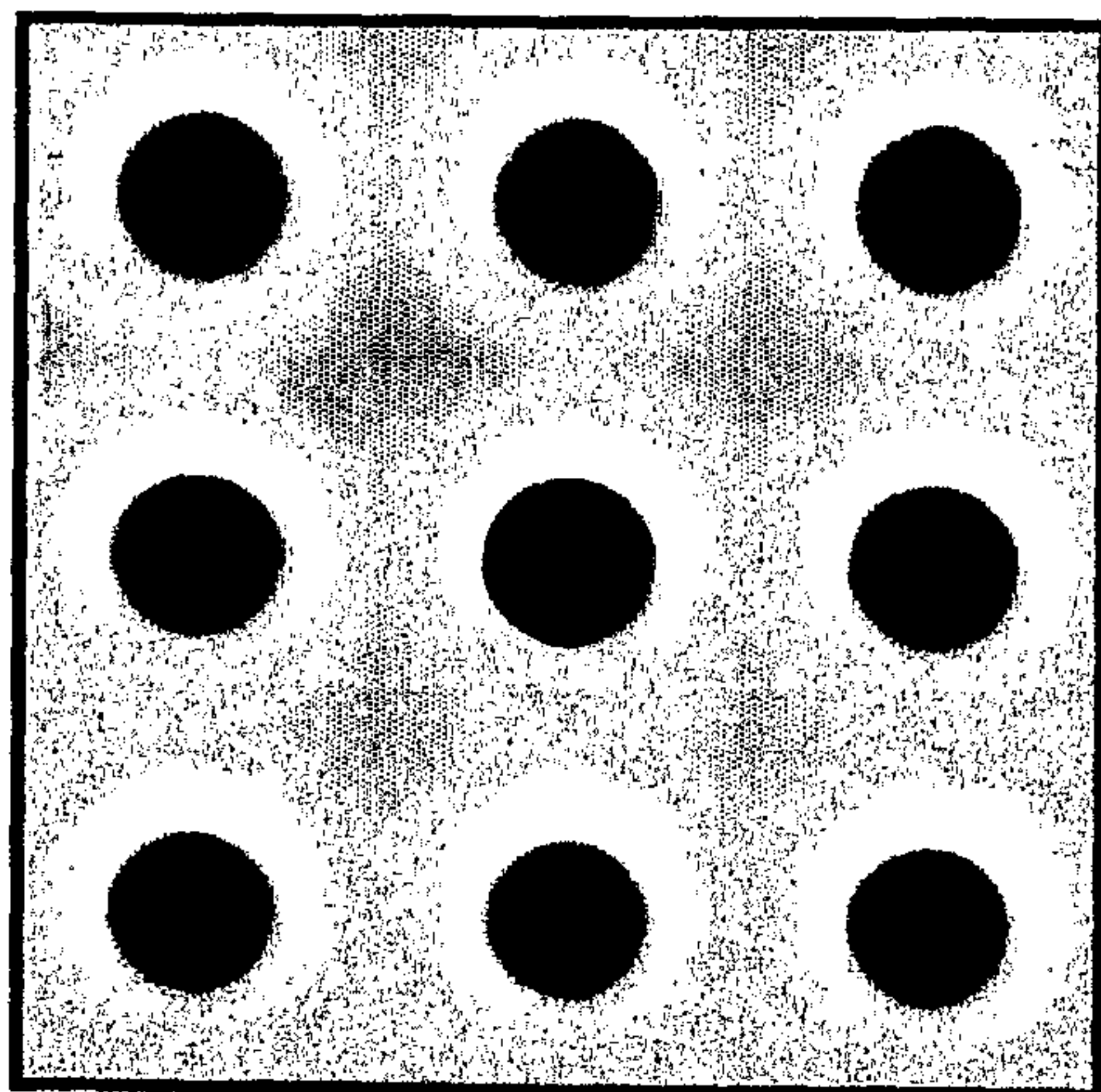
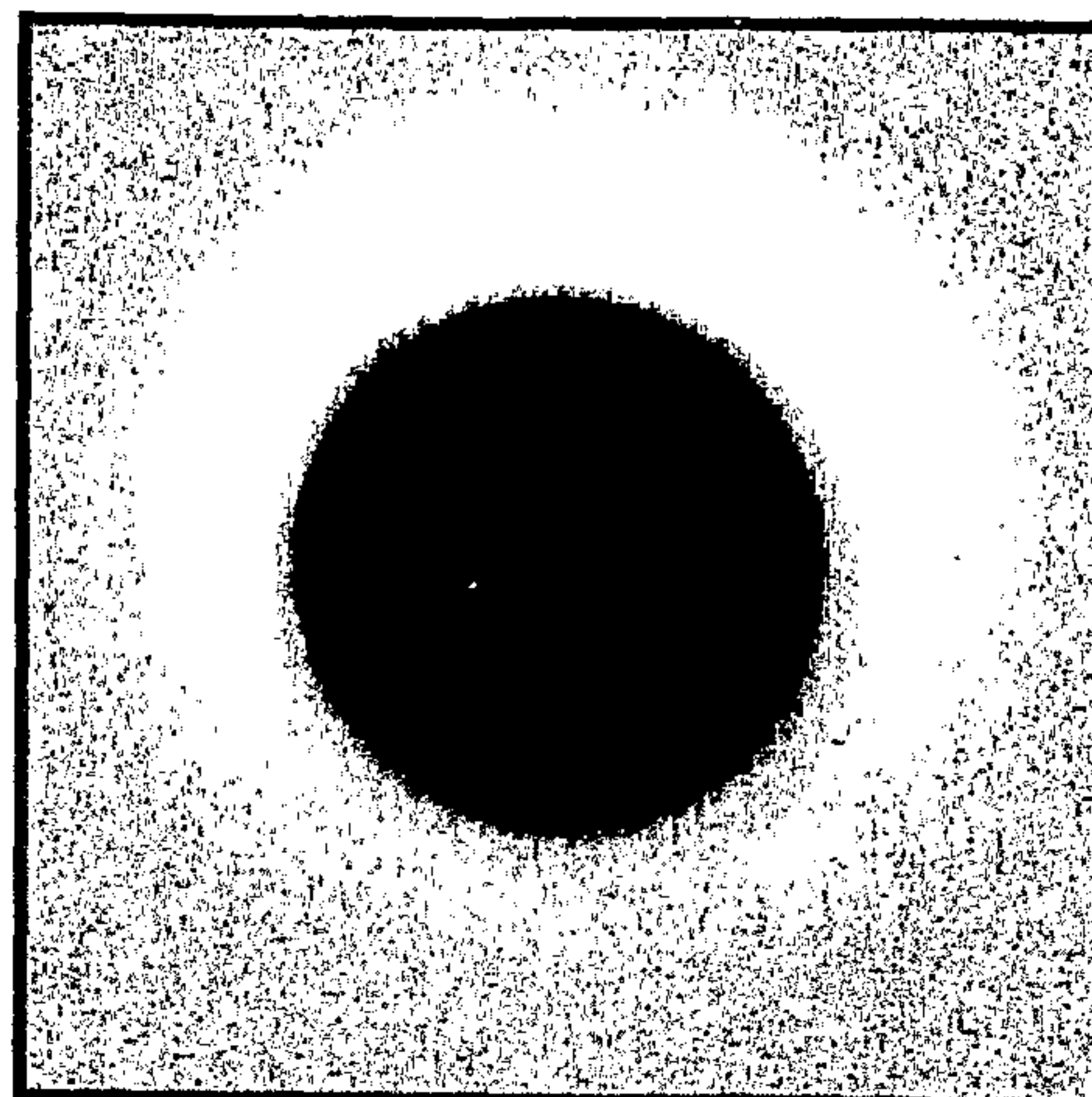
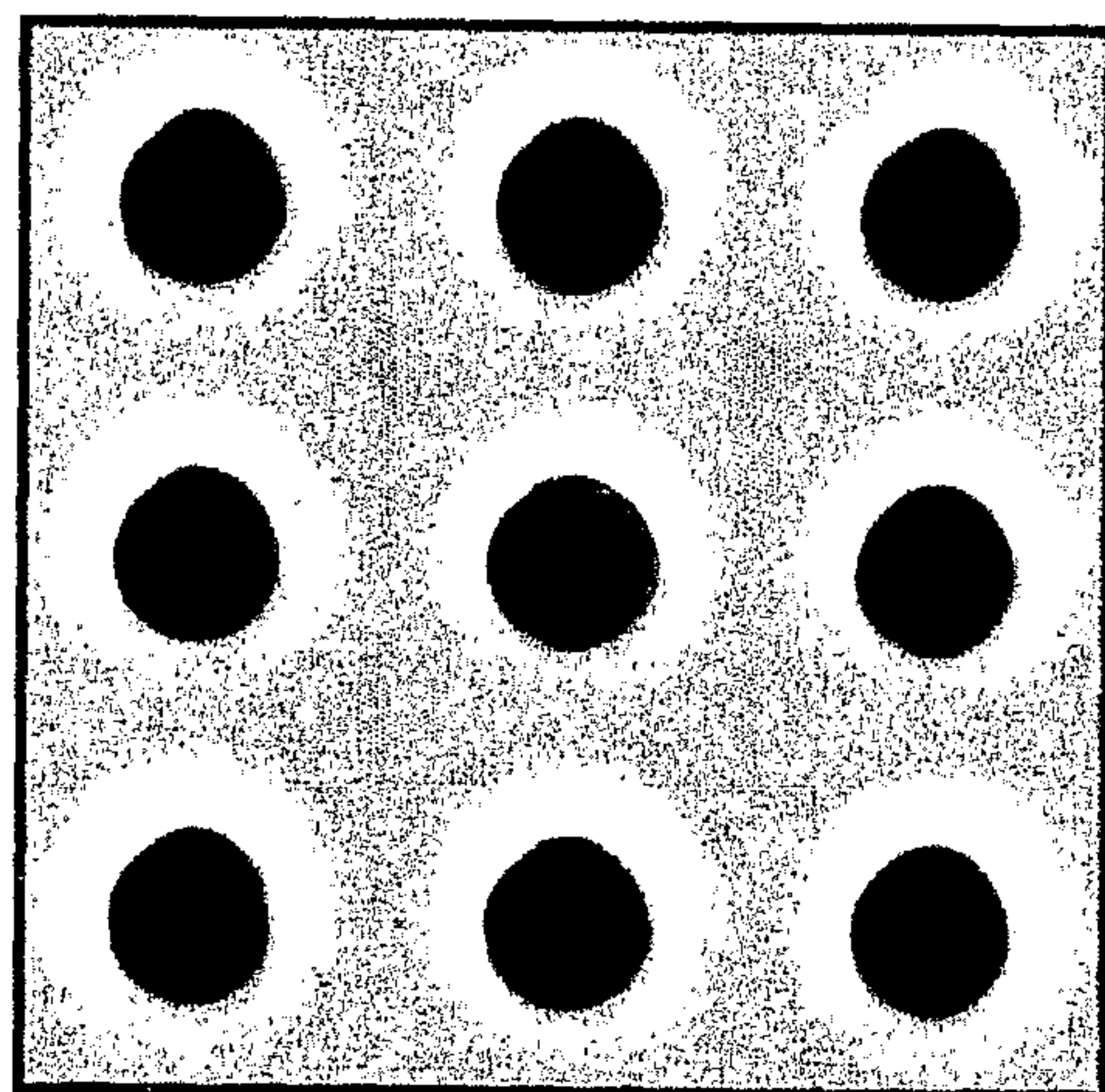
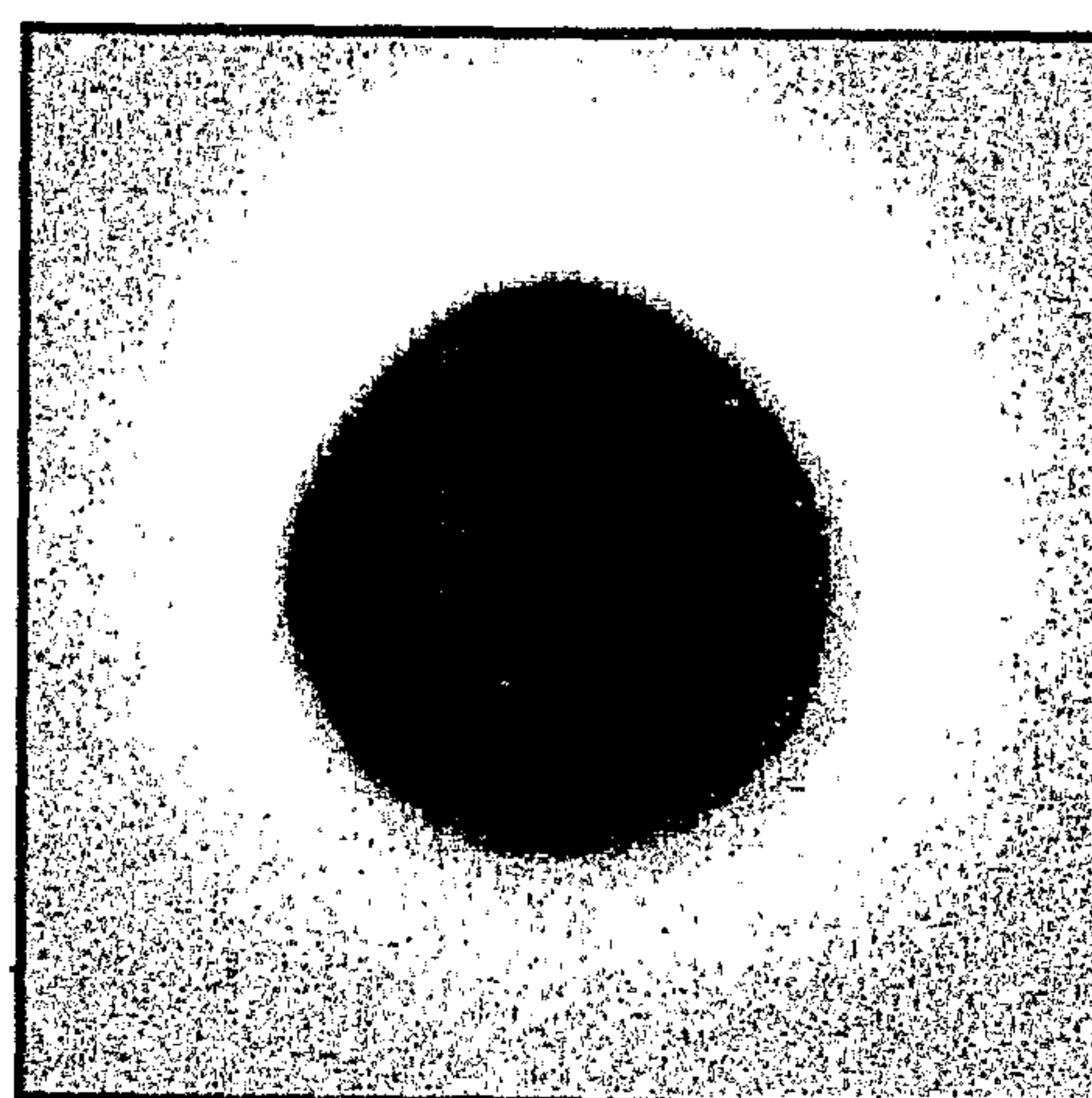
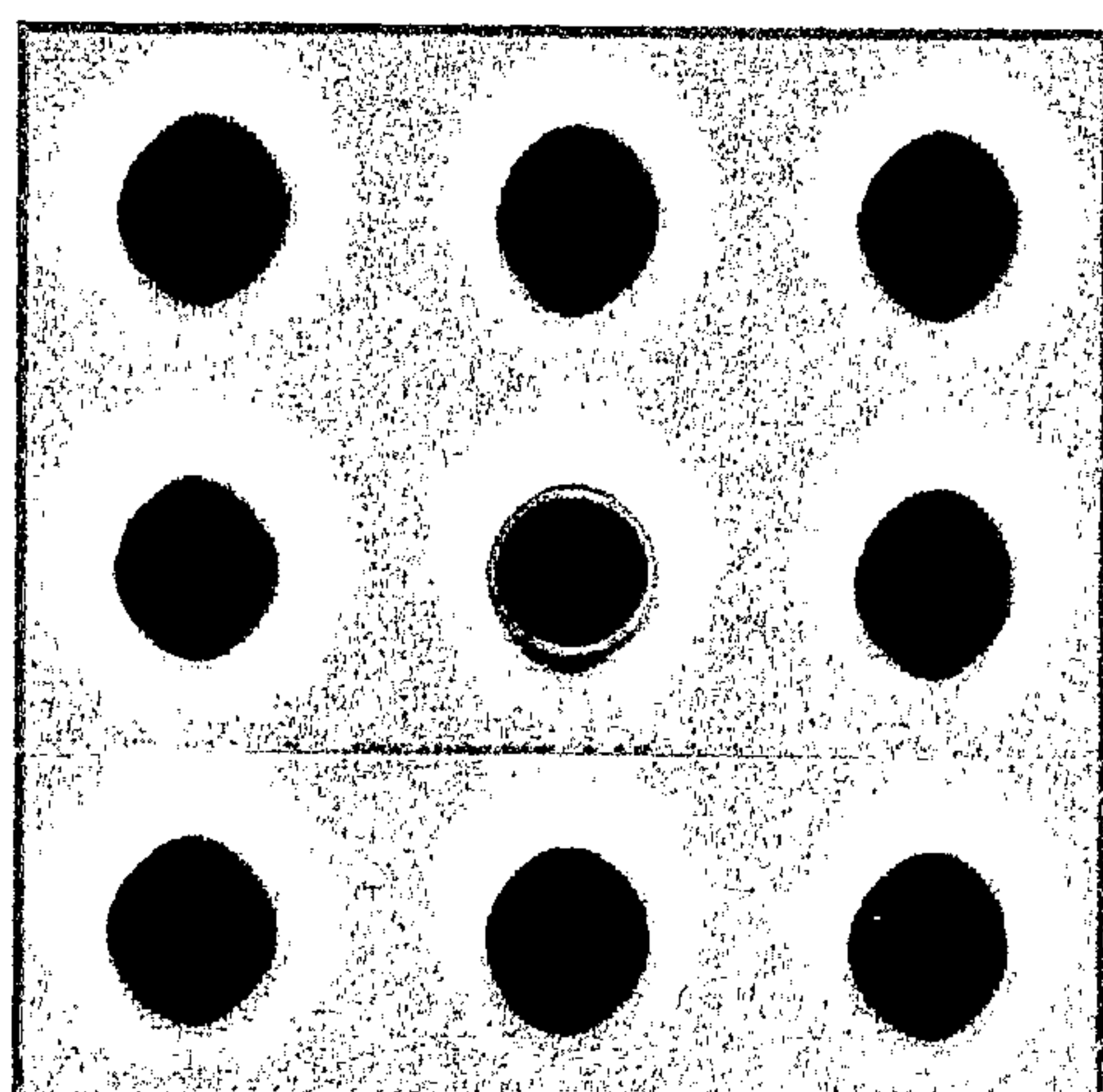
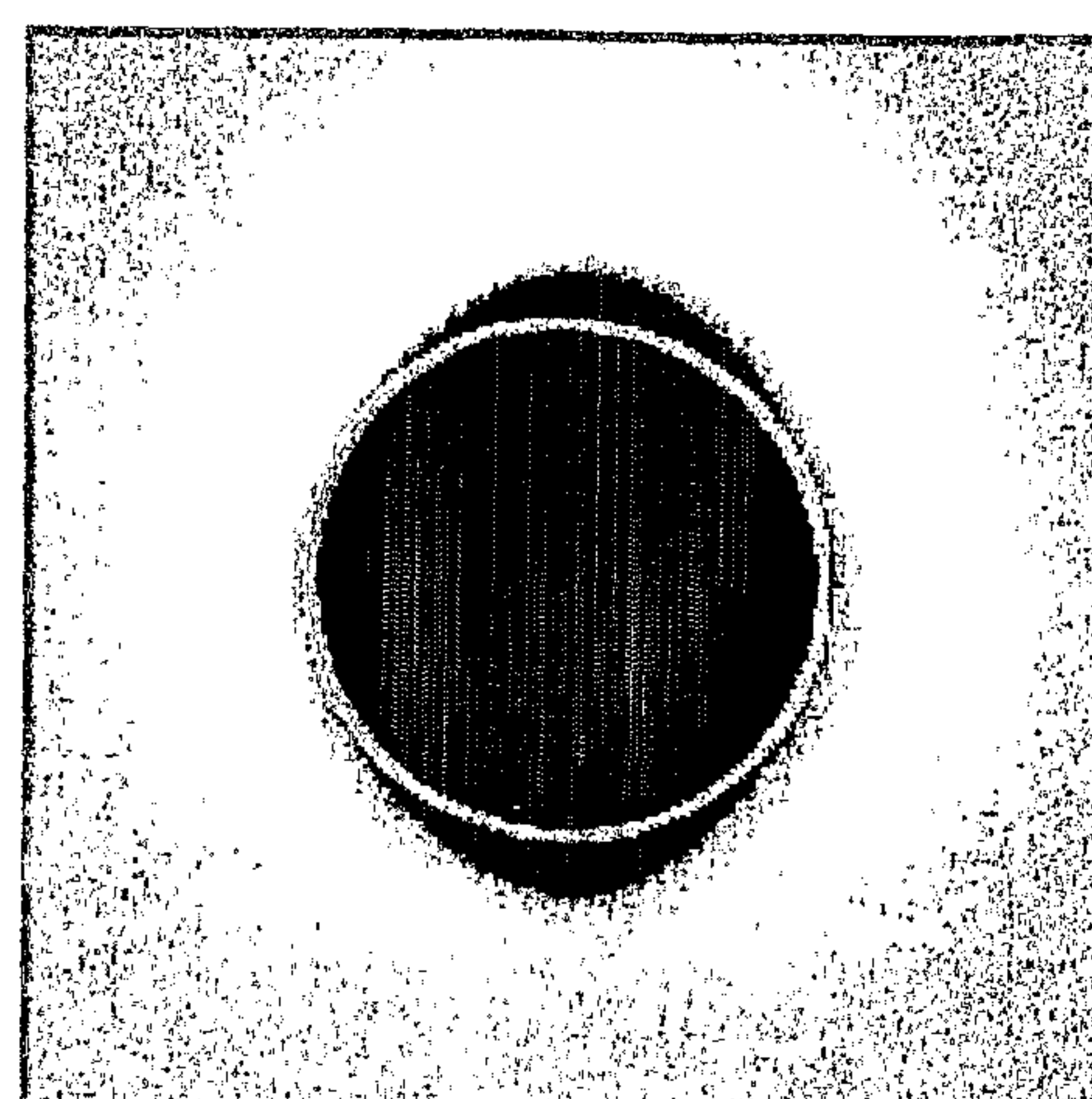


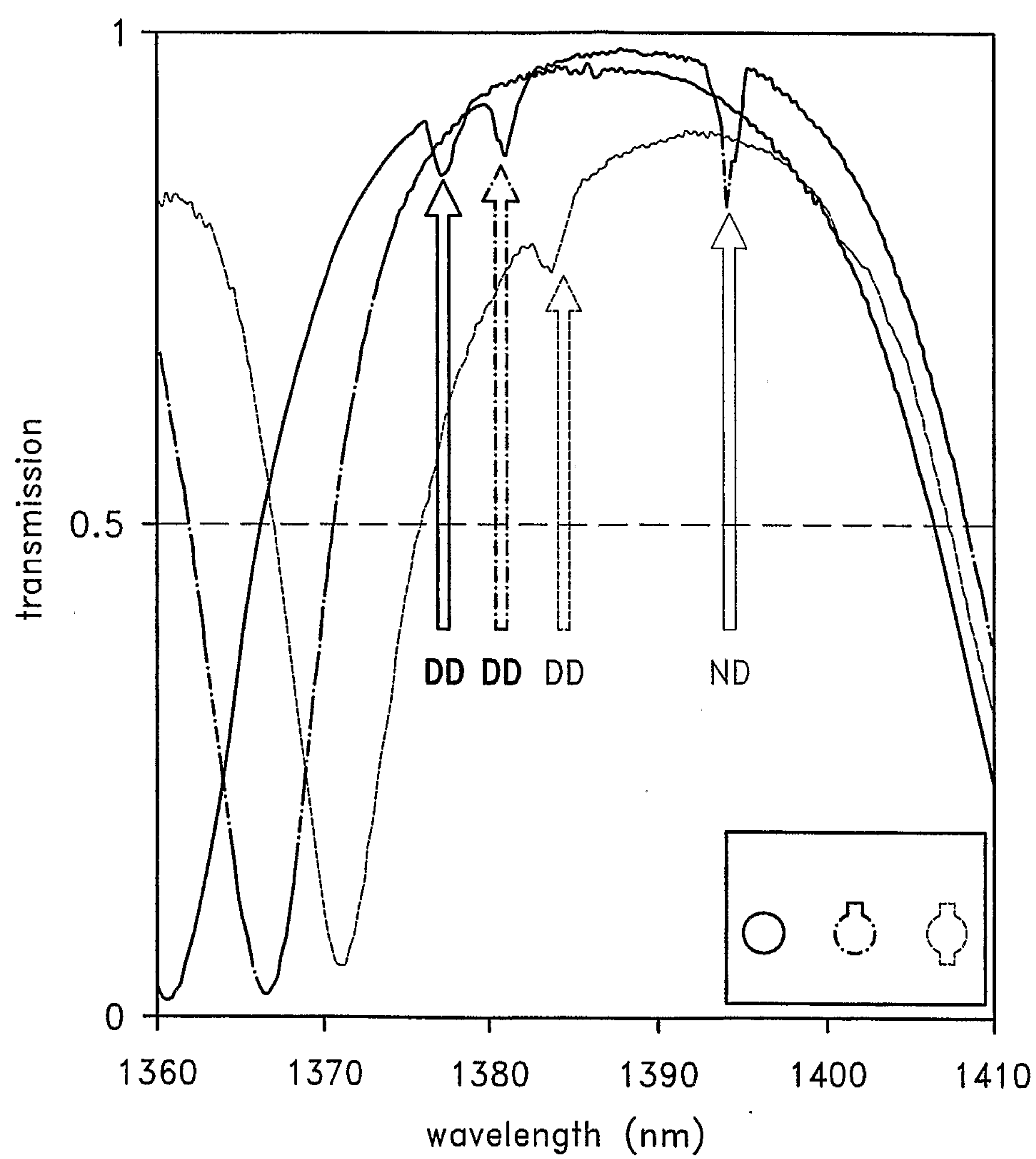
FIG. 20A

FIG. 20B

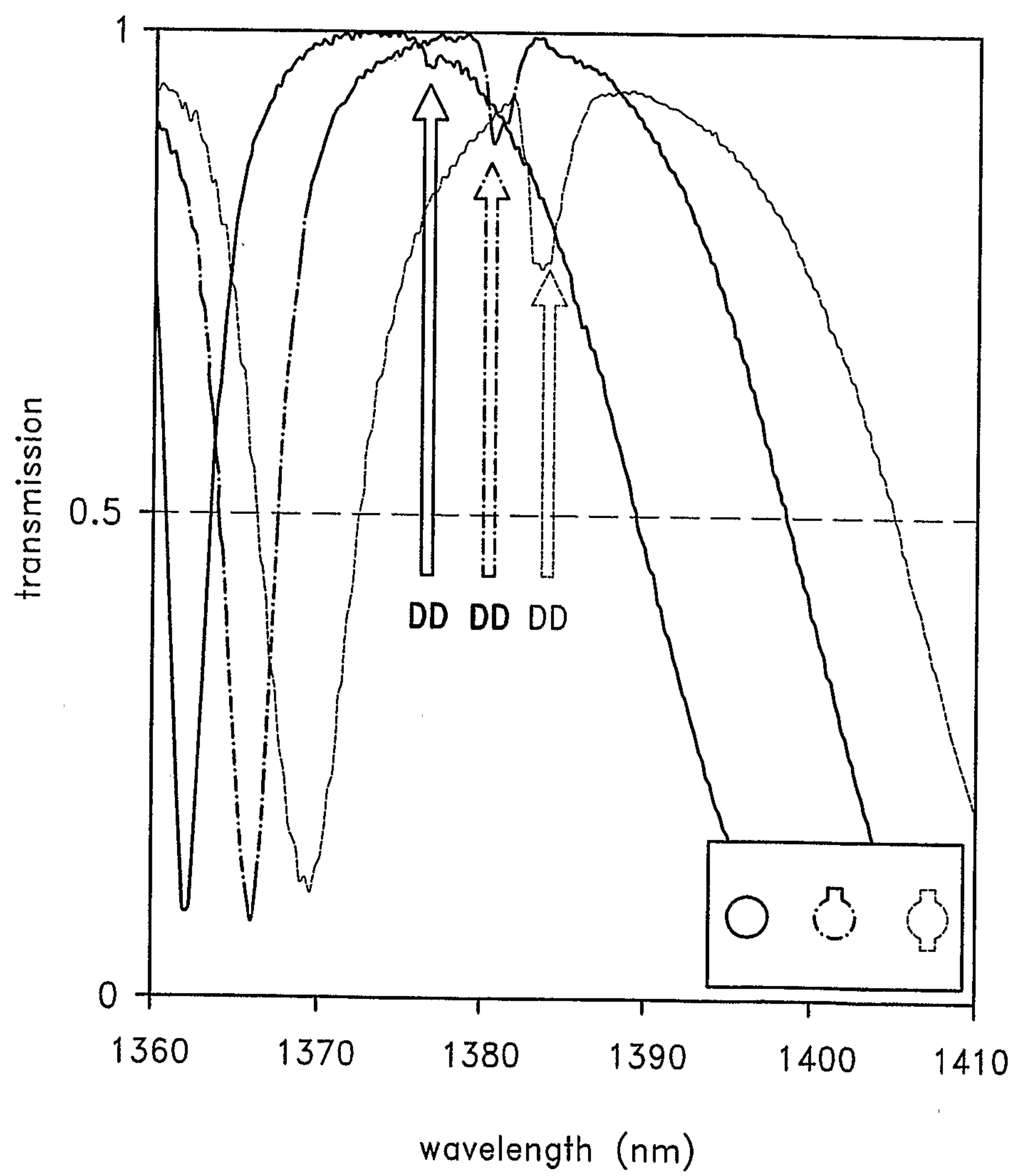
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*FIG. 21A**FIG. 21D**FIG. 21B**FIG. 21E**FIG. 21C**FIG. 21F*

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*FIG. 22A*

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*FIG. 22B*

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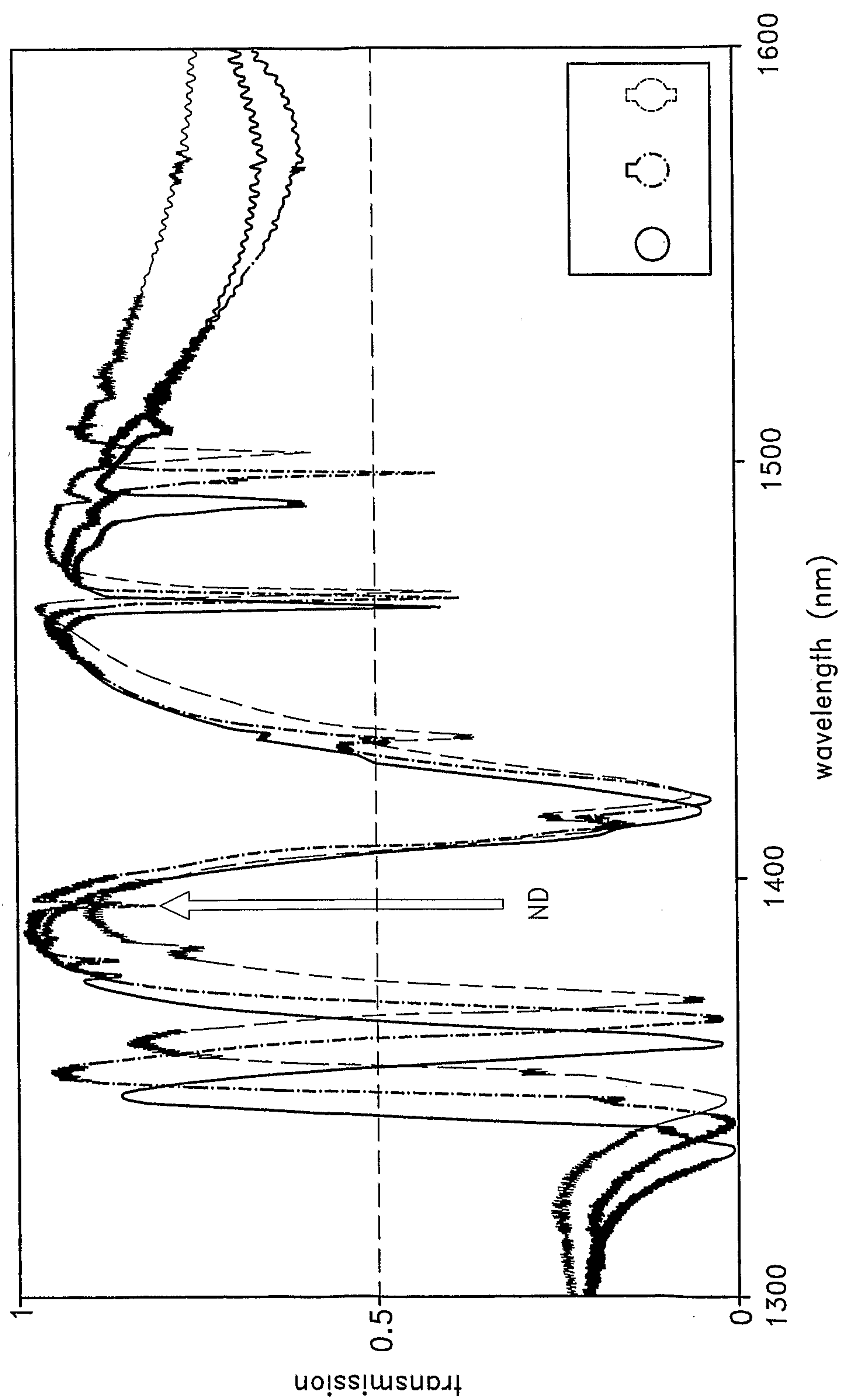


FIG. 23

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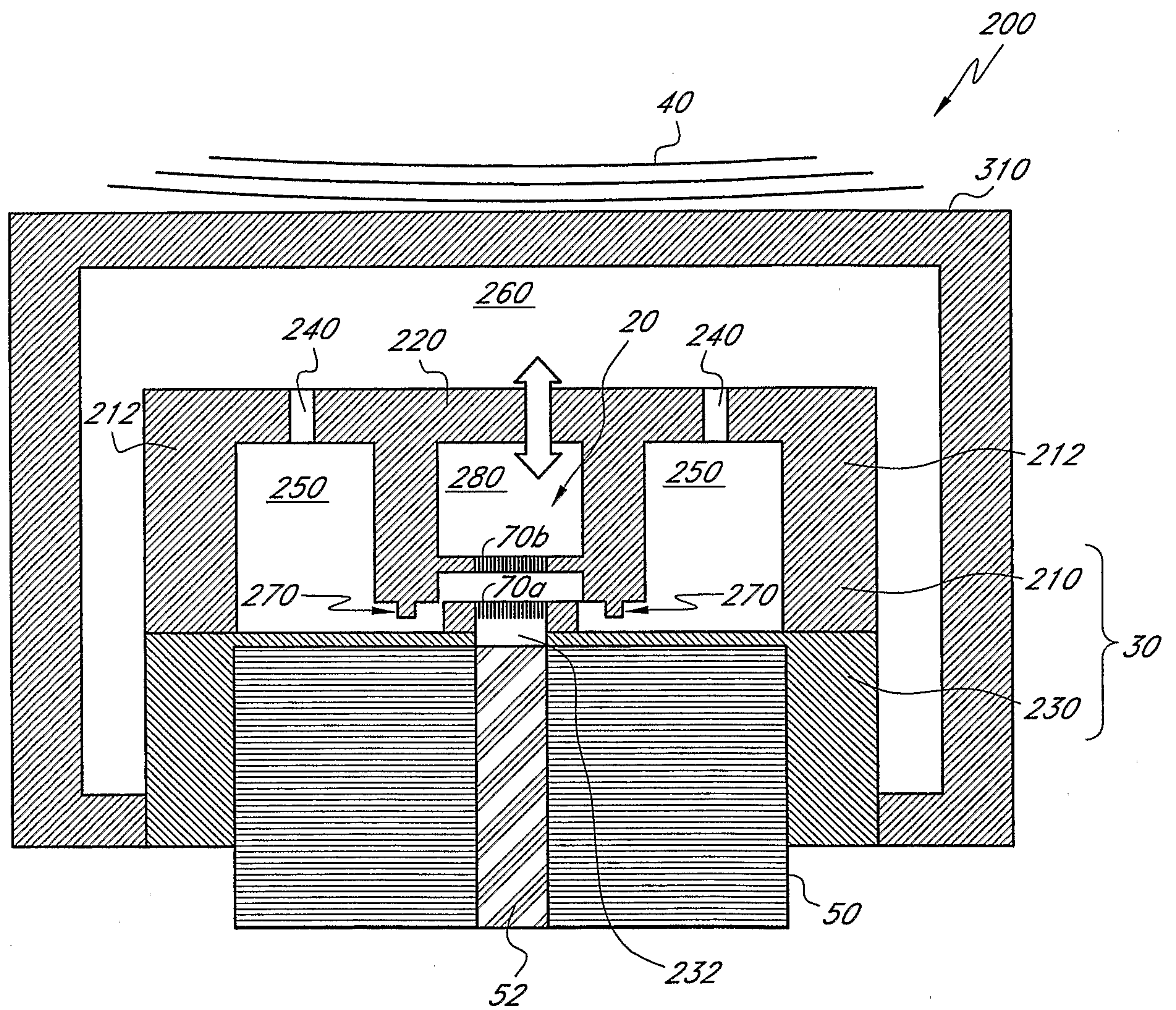


FIG. 25

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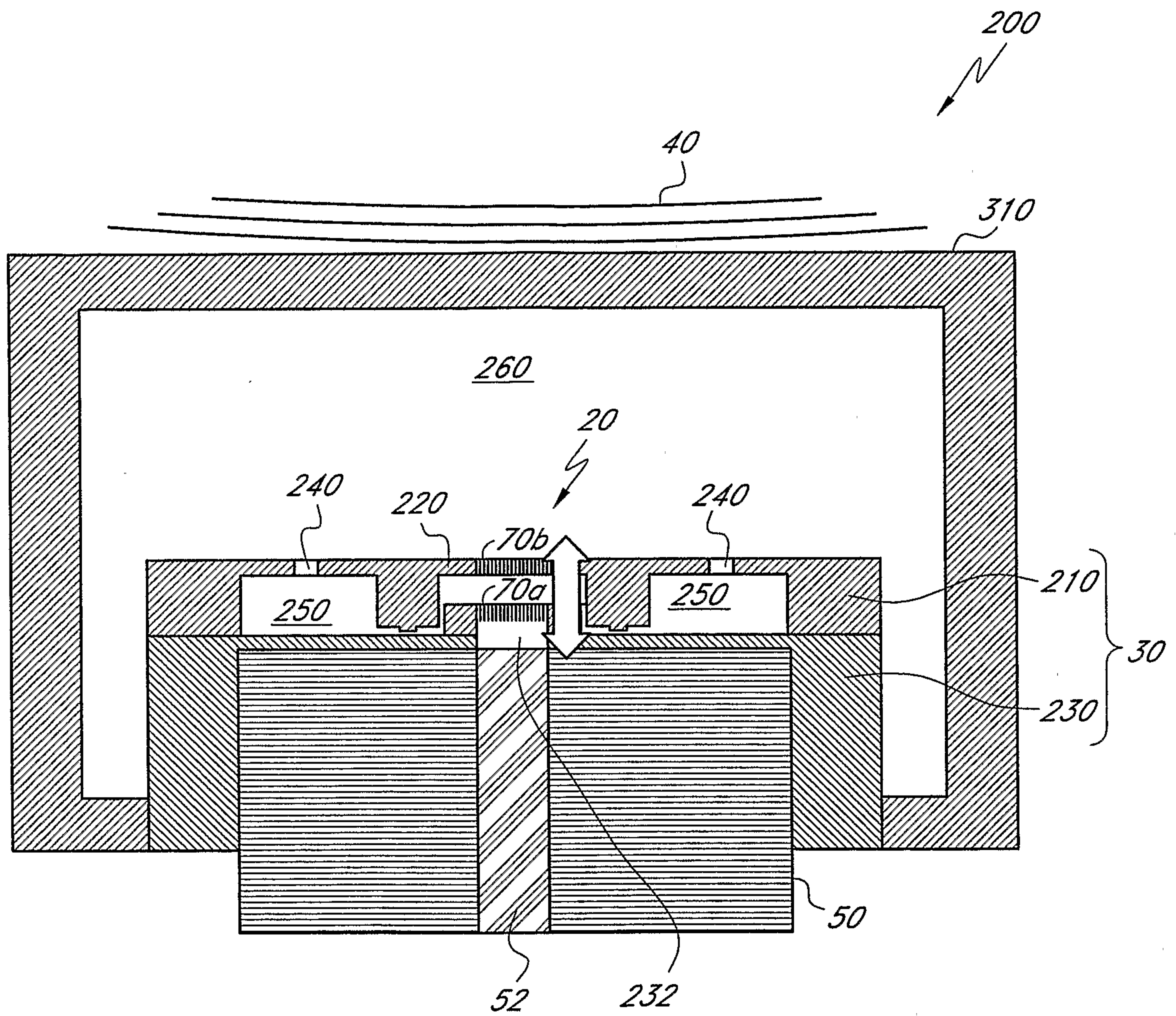


FIG. 26

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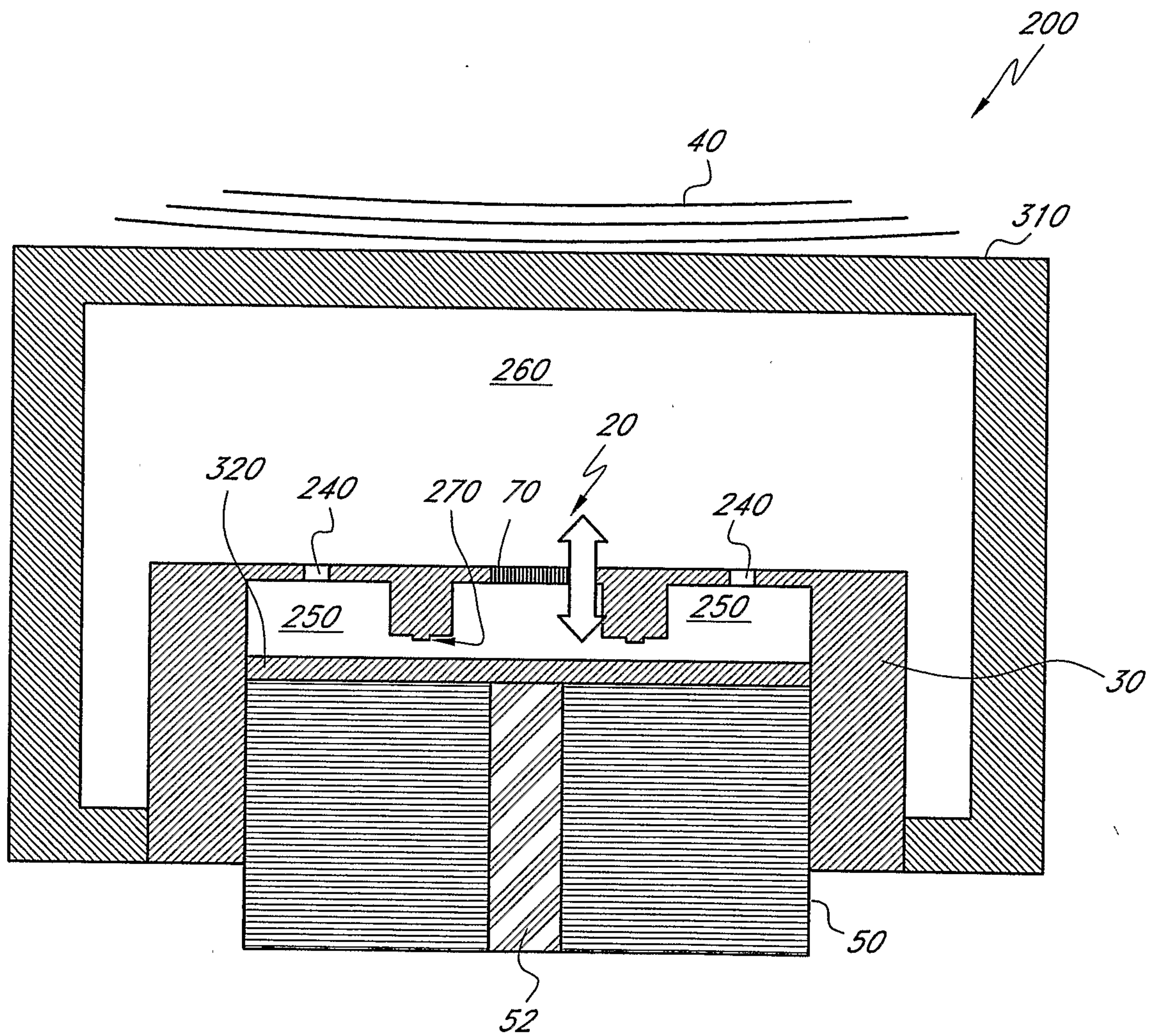


FIG. 27

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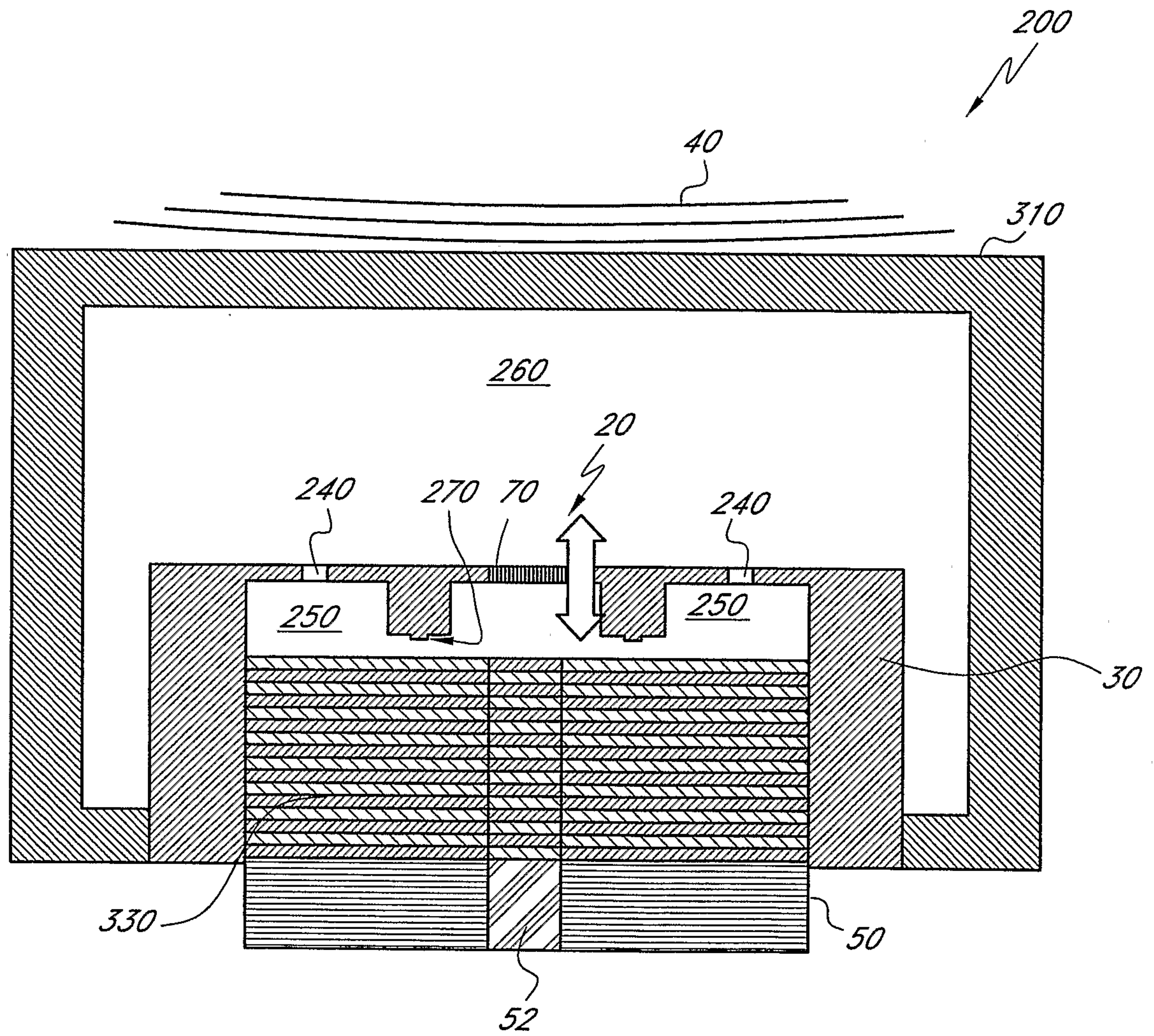


FIG. 28

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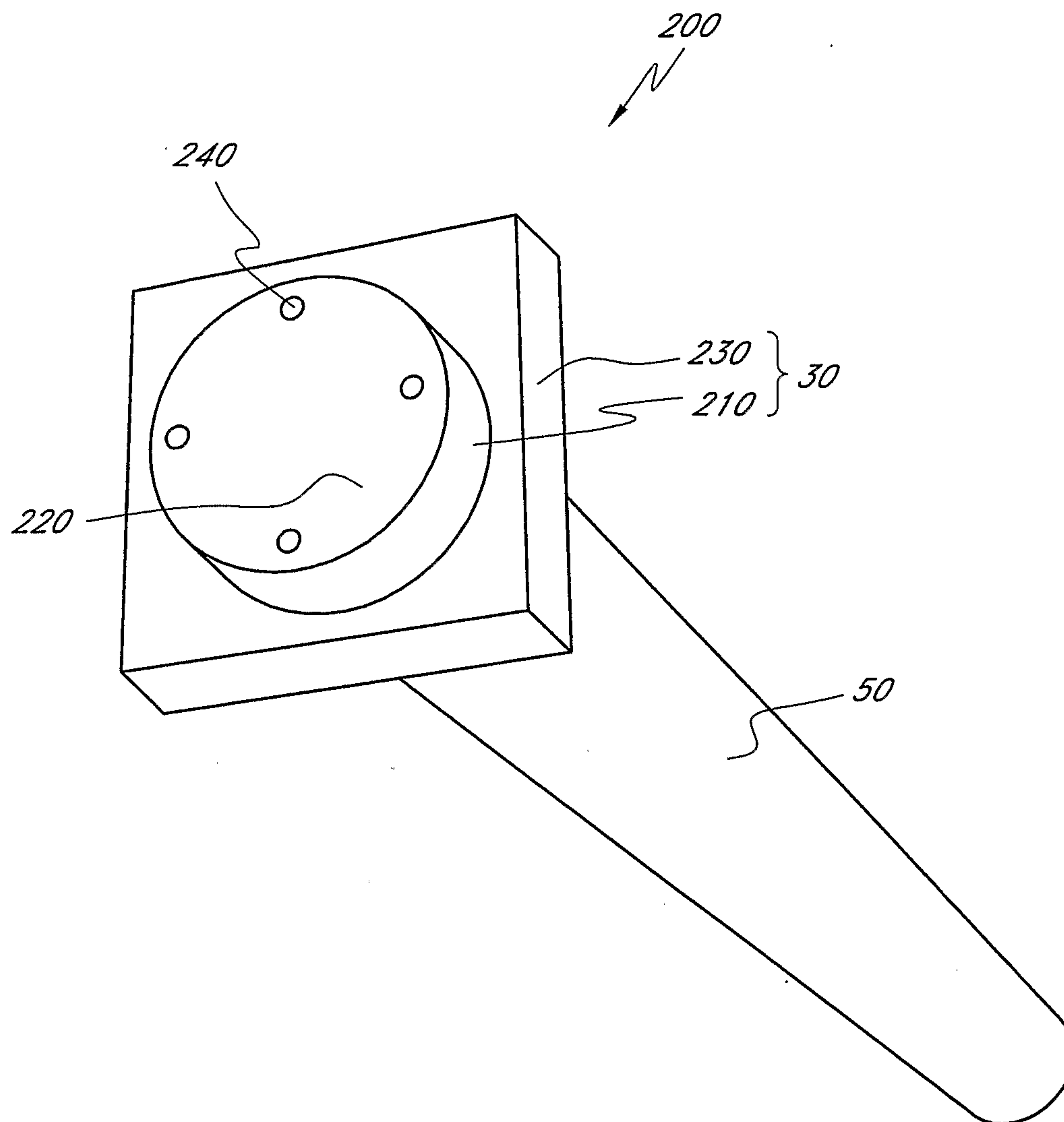
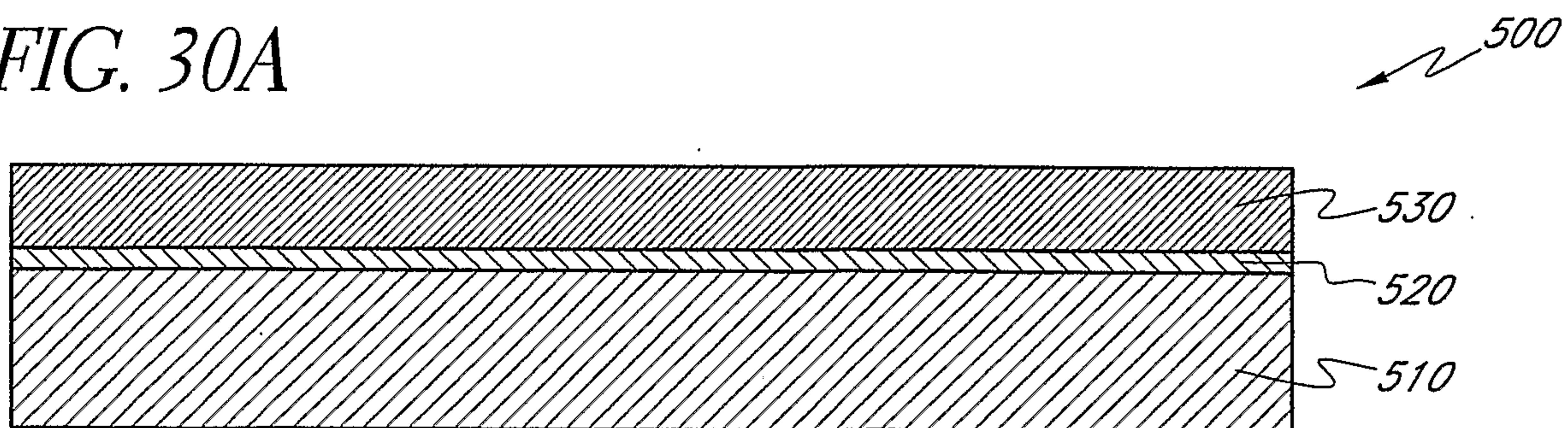
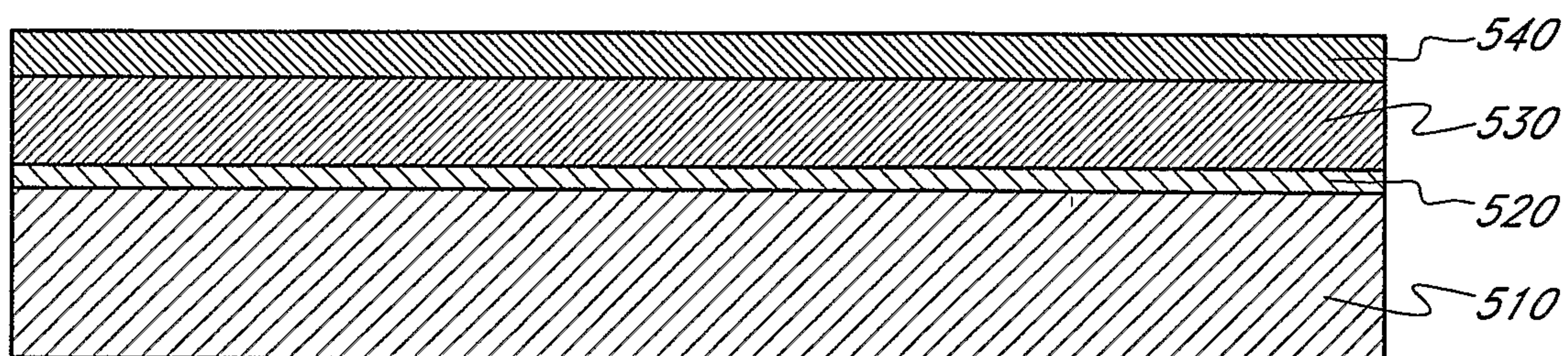
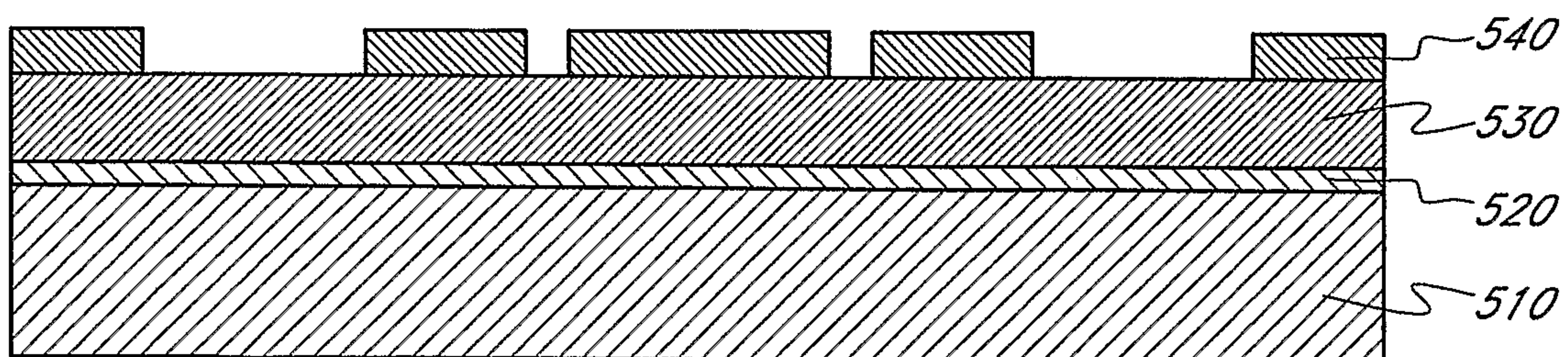
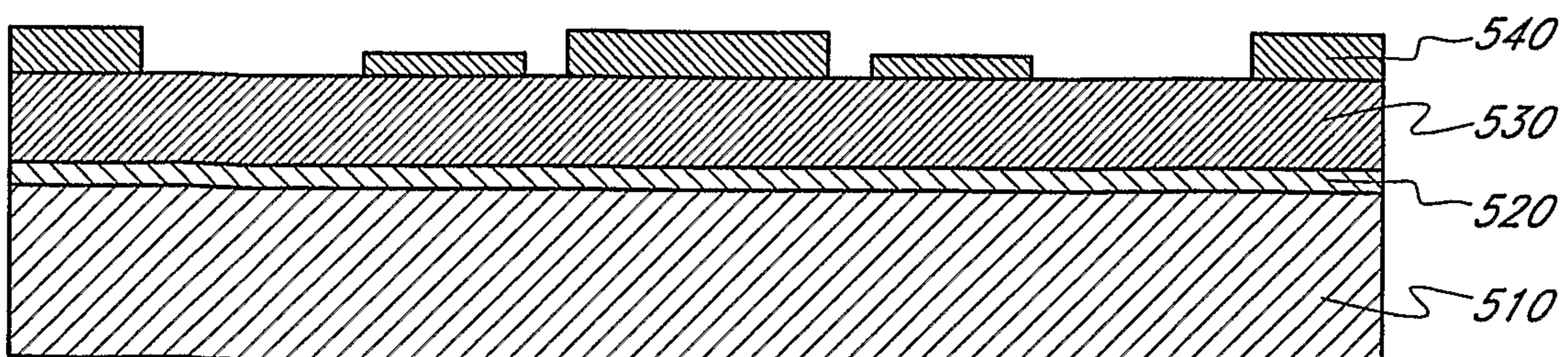
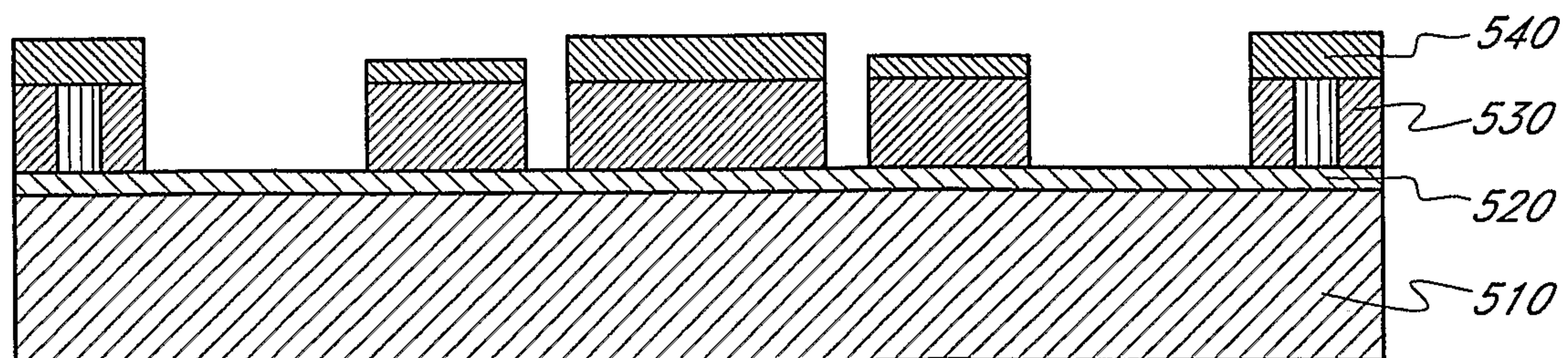
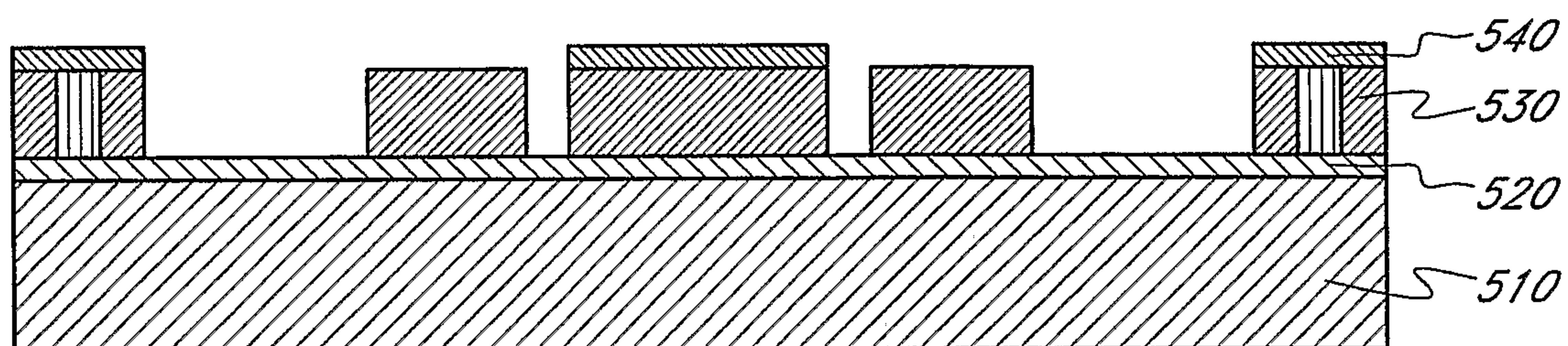
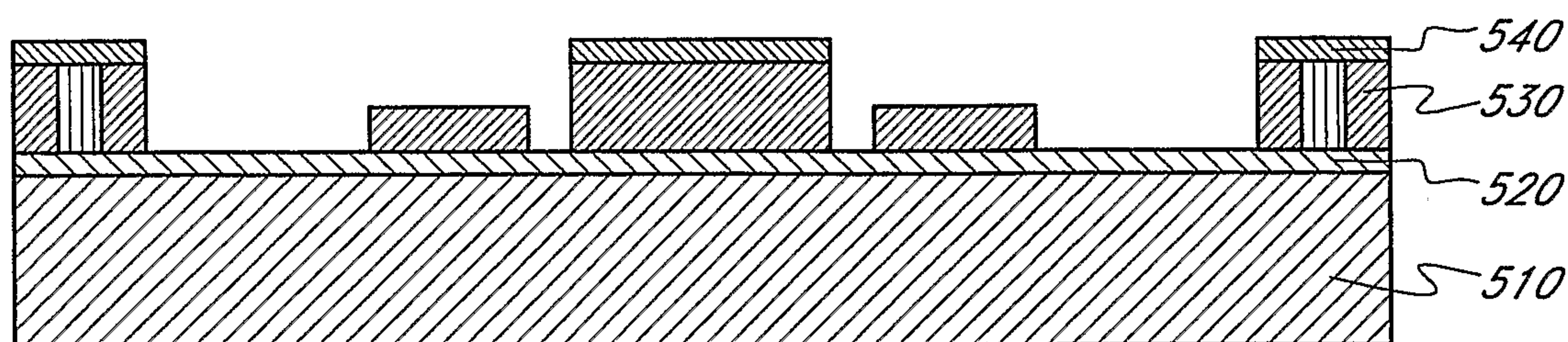
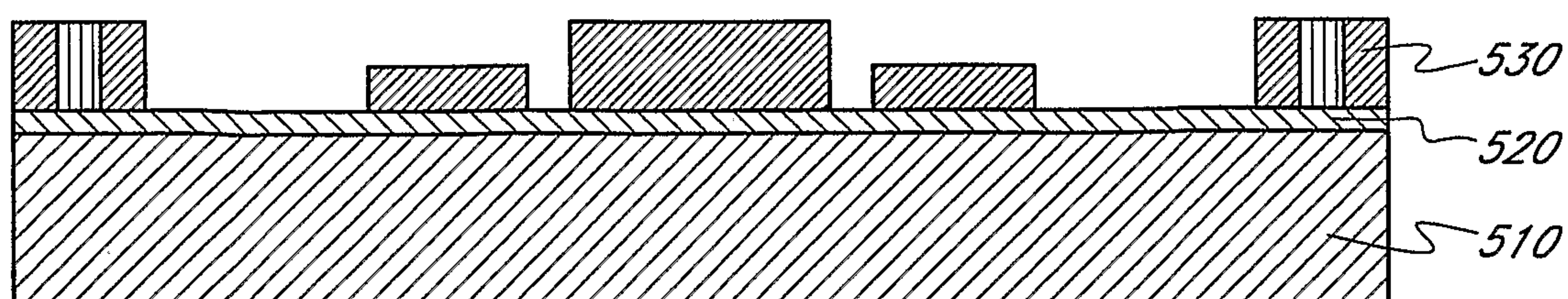


FIG. 29

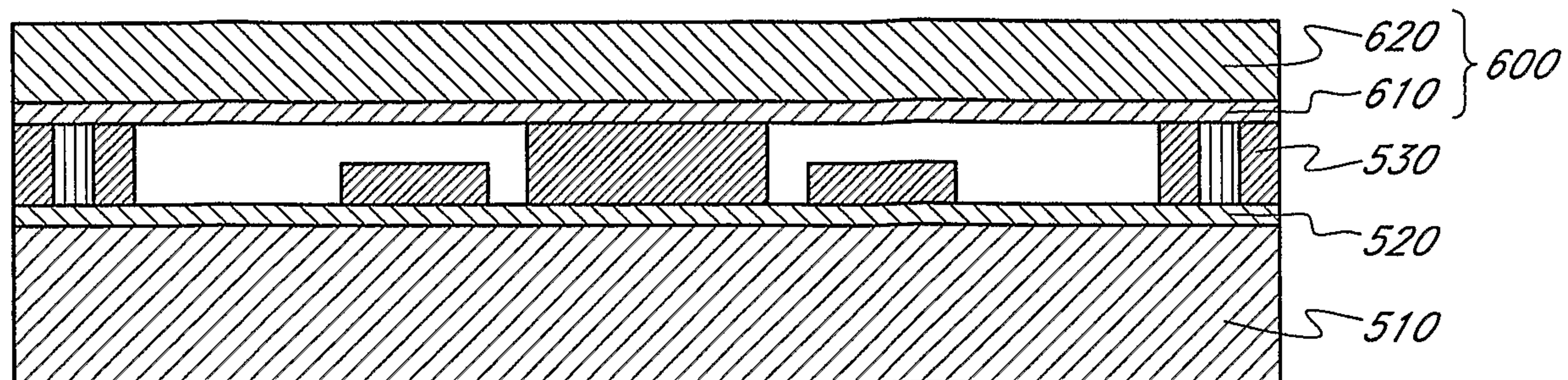
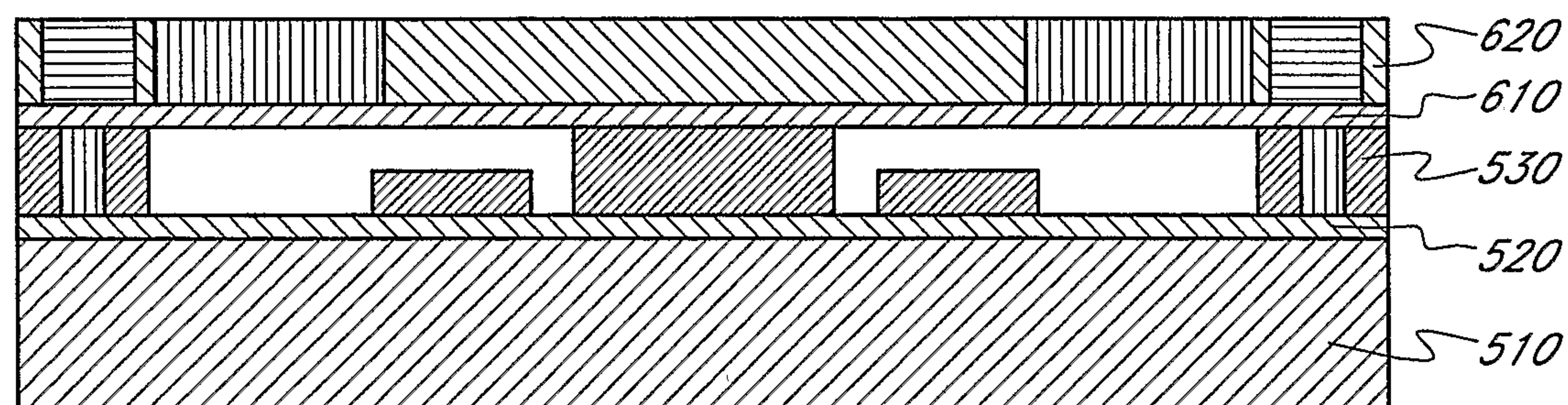
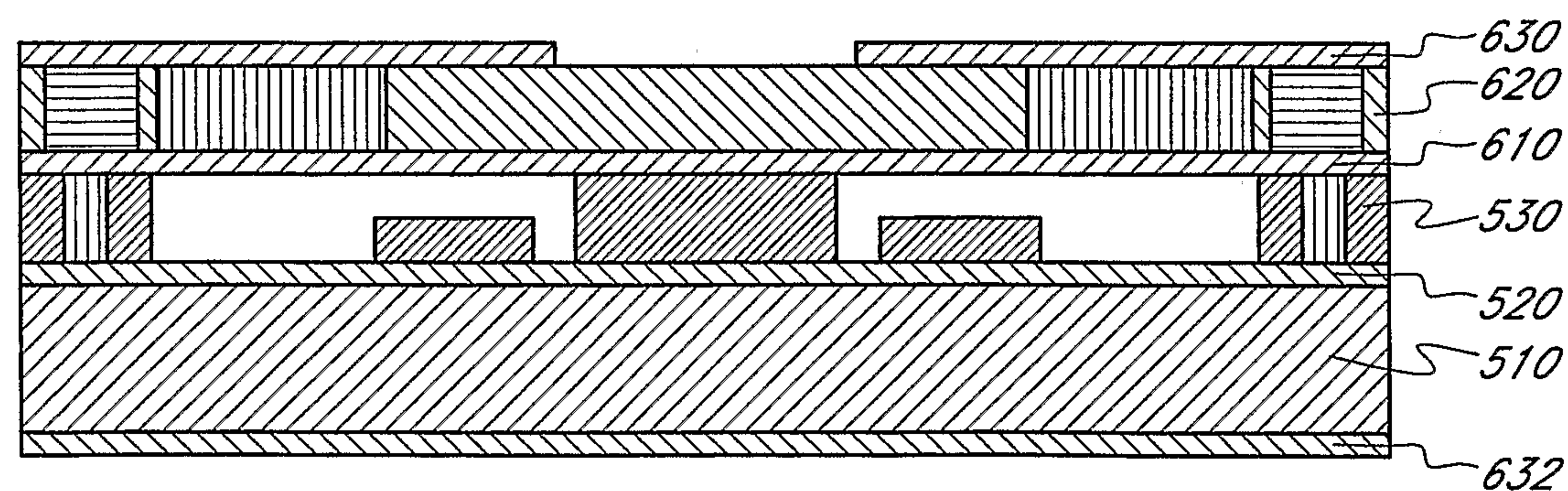
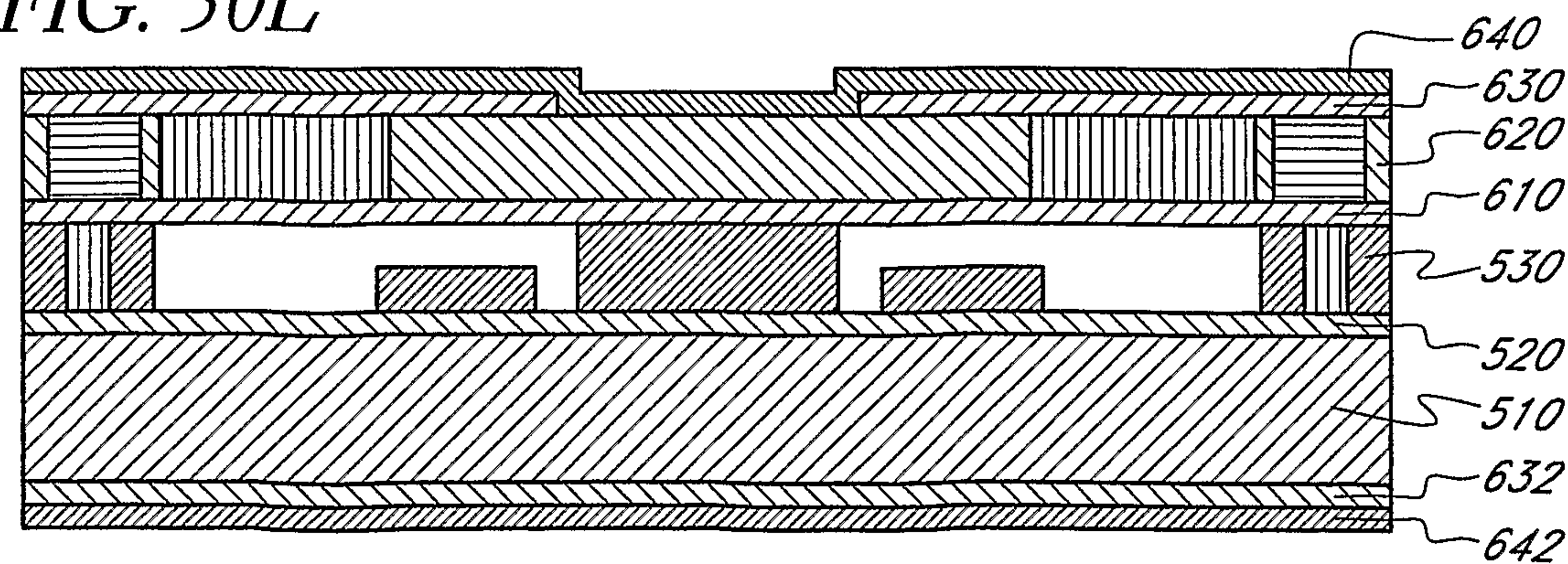
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FIG. 30A*FIG. 30B**FIG. 30C**FIG. 30D*

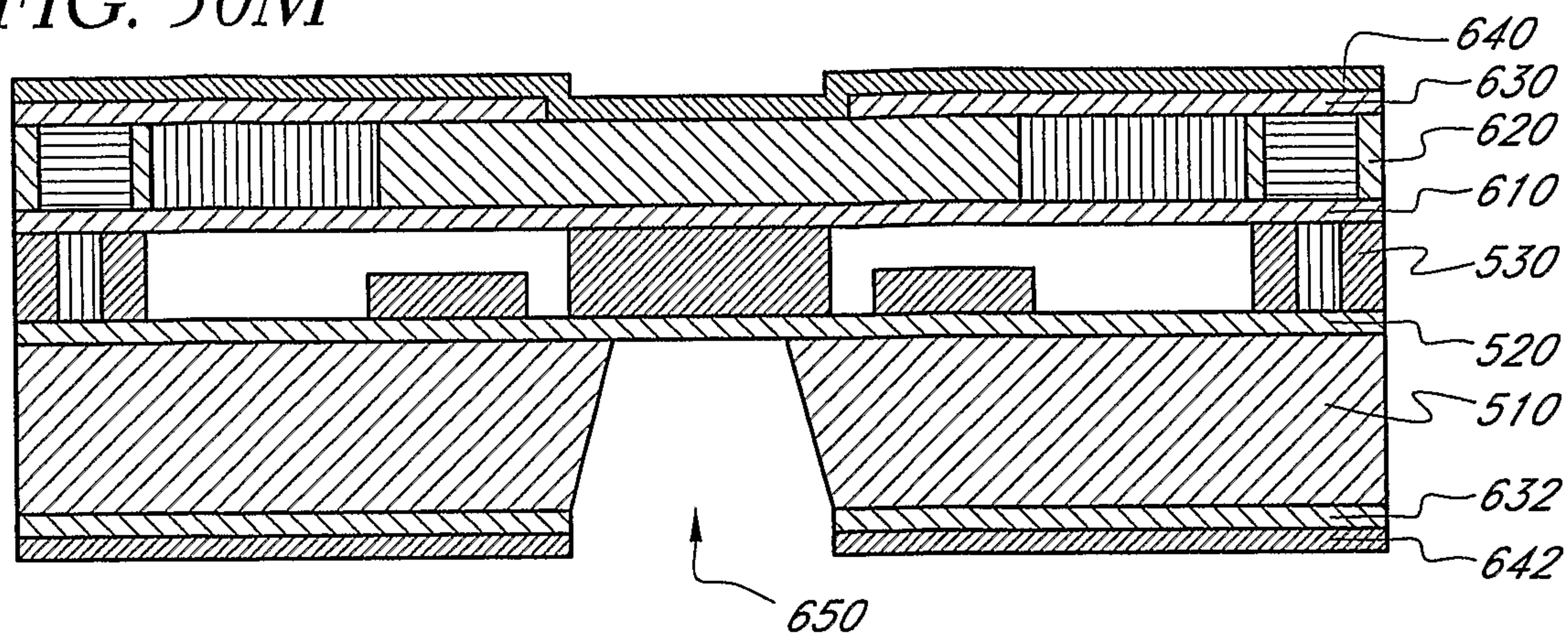
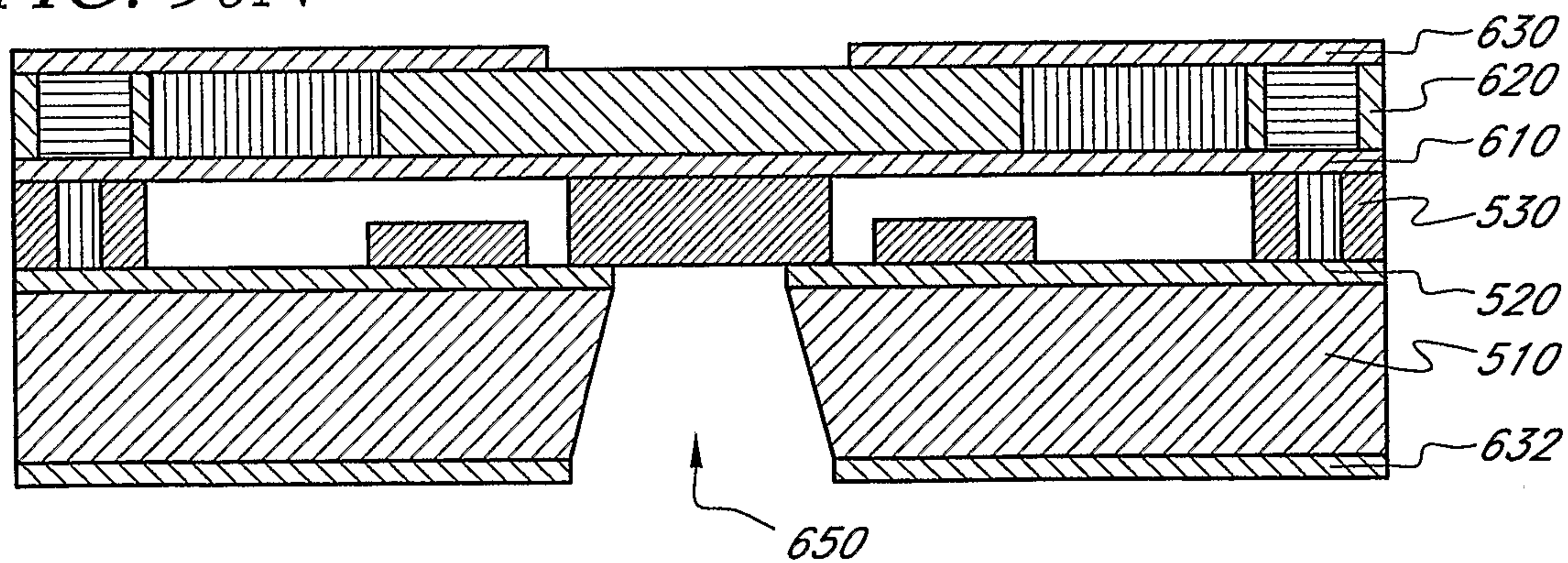
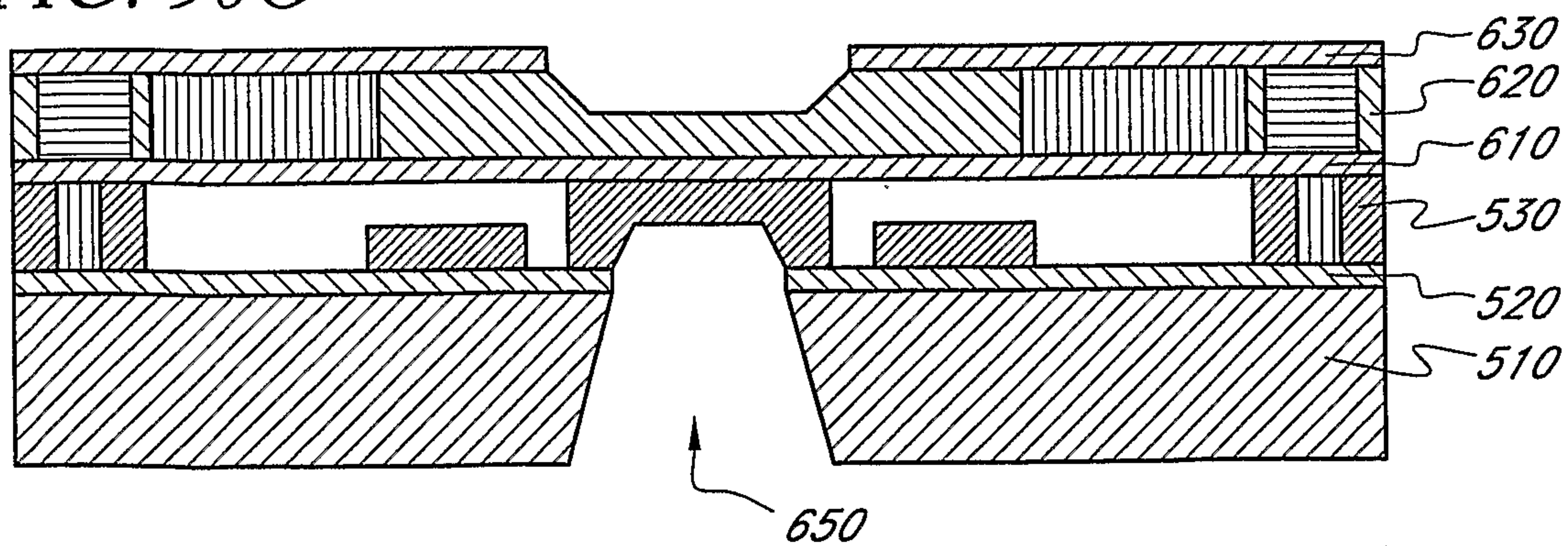
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FIG. 30E*FIG. 30F**FIG. 30G**FIG. 30H*

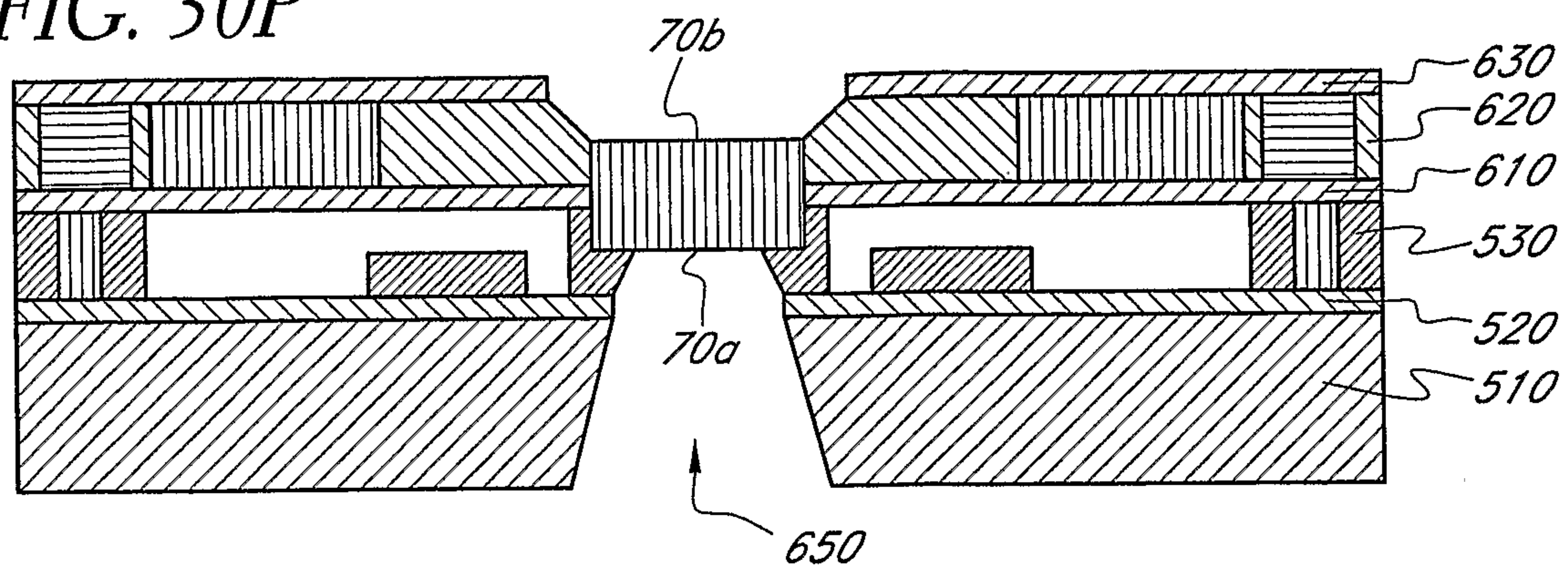
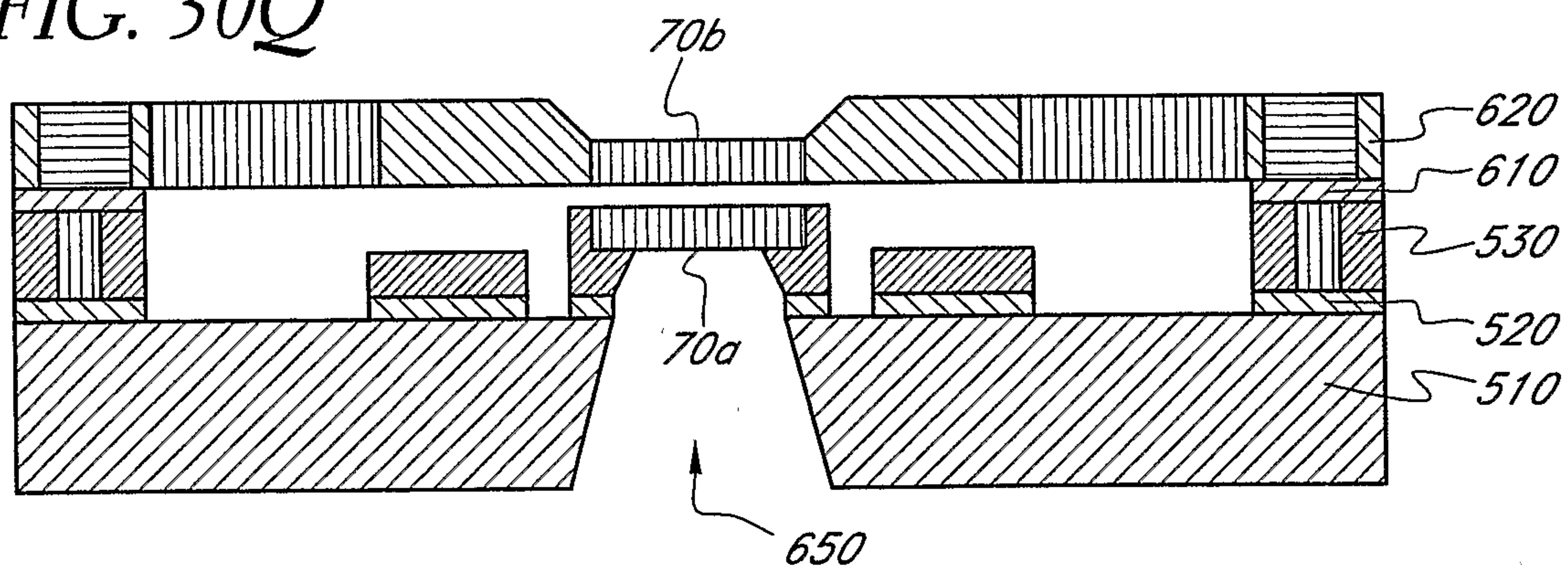
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FIG. 30I*FIG. 30J**FIG. 30K**FIG. 30L*

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FIG. 30M*FIG. 30N**FIG. 30O*

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FIG. 30P*FIG. 30Q*

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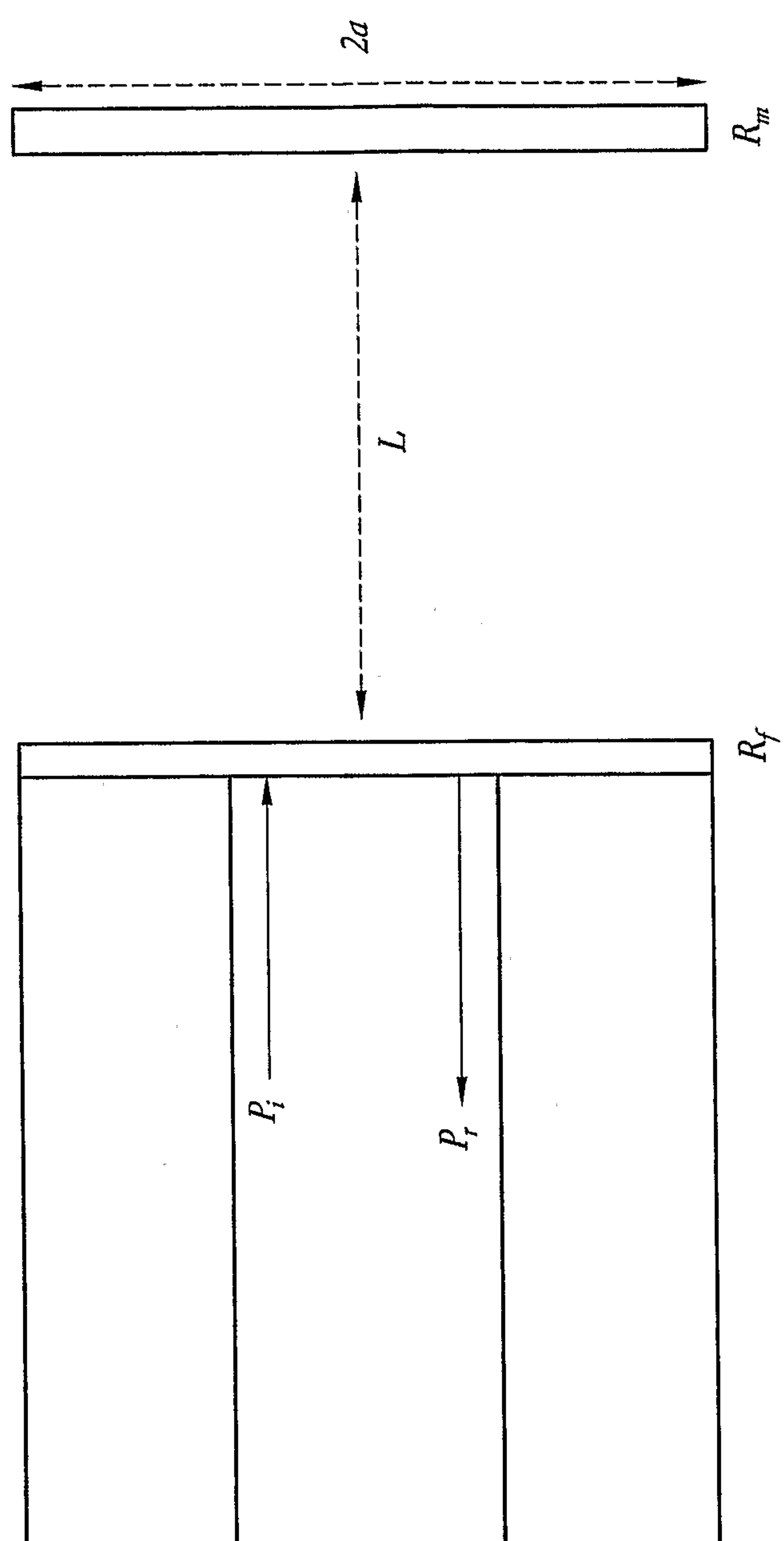
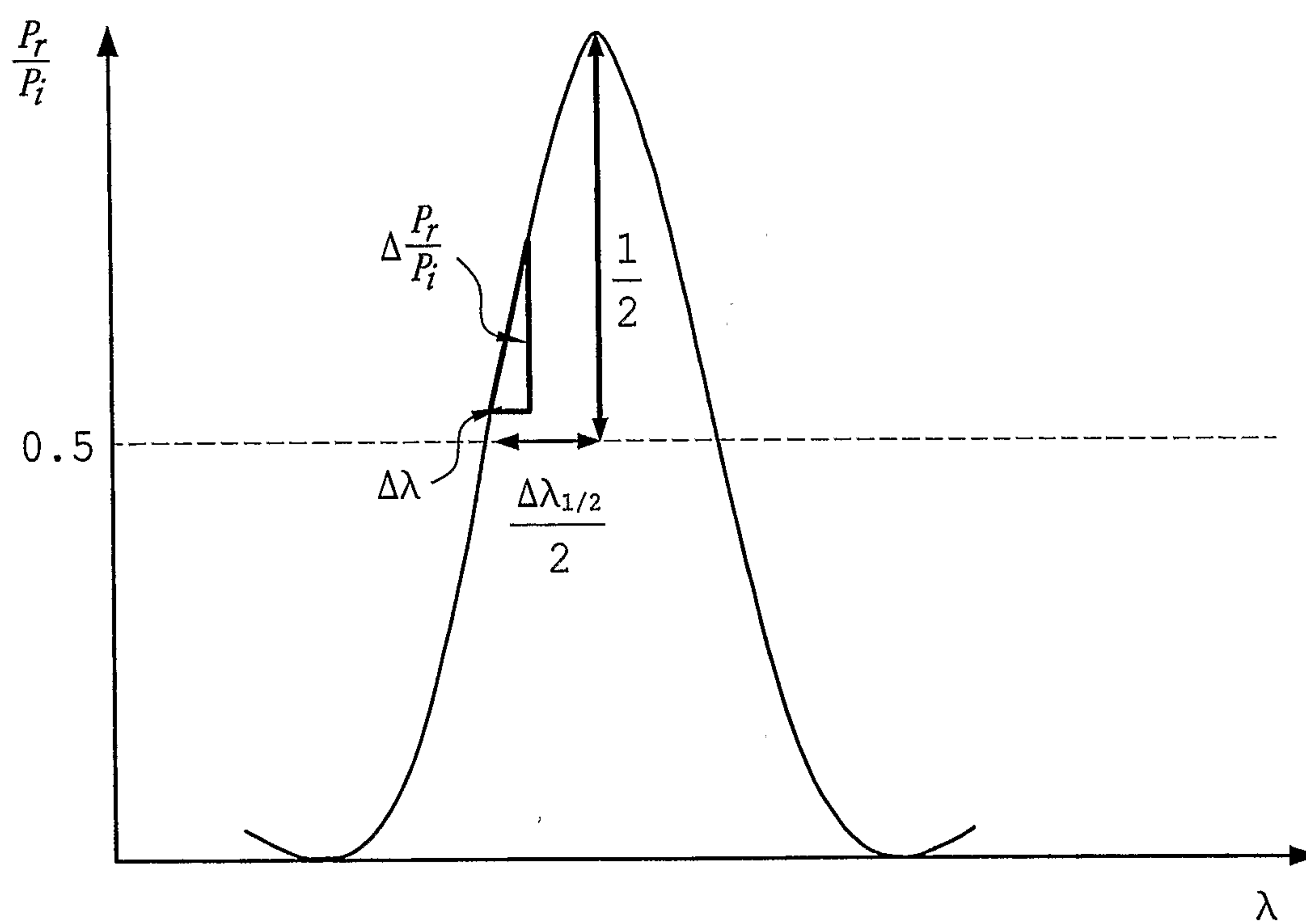


FIG. 31

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*FIG. 32*

