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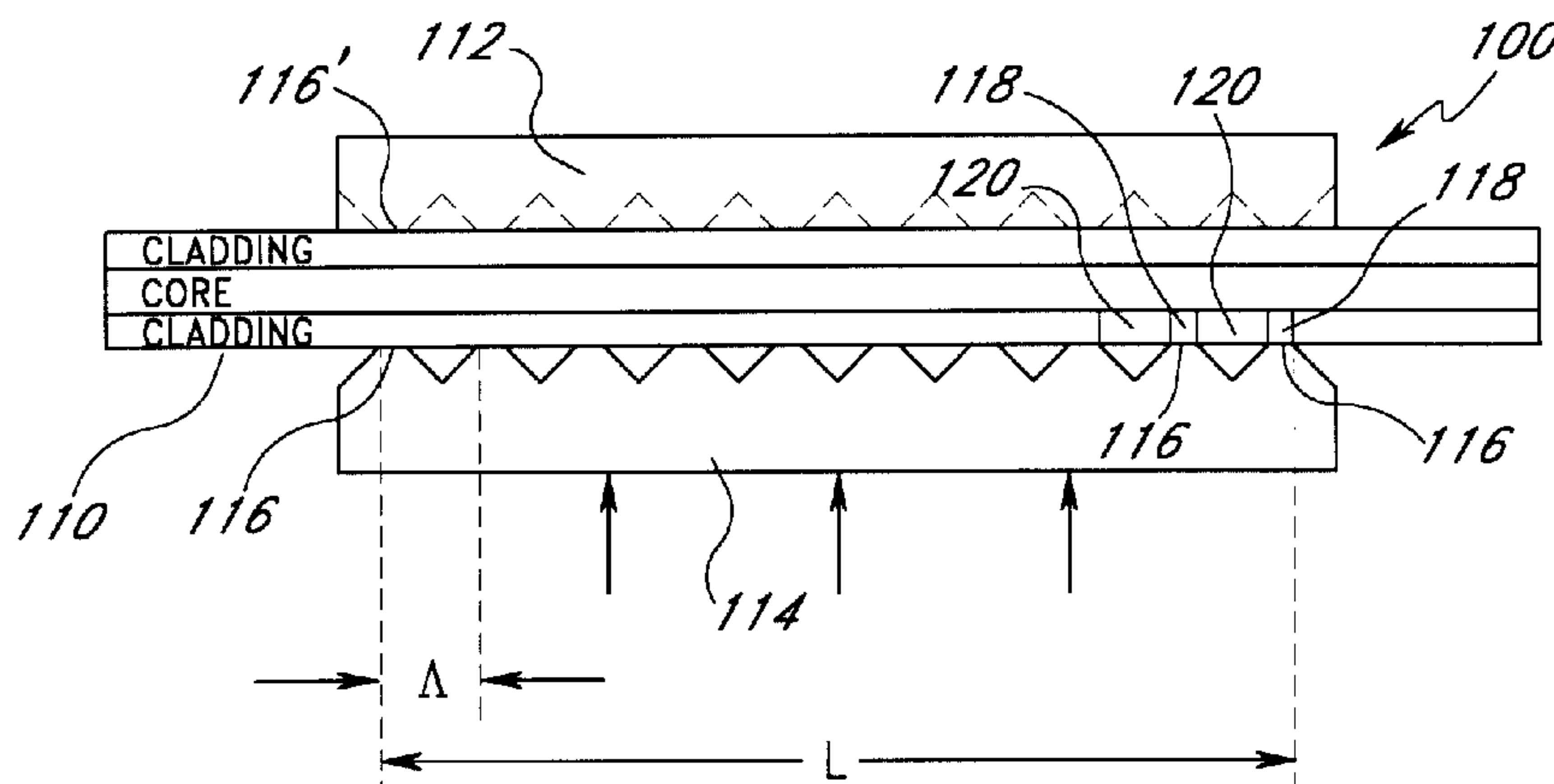
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(54) **RESEAU DE FIBRES ACCORDABLE, A LONGUE PERIODE
INDUITE MECANIQUEMENT, AYANT DES
CARACTERISTIQUES DE POLARISATION AMELIOREES**

(54) **TUNABLE, MECHANICALLY INDUCED LONG-PERIOD FIBER
GRATING WITH ENHANCED POLARIZING
CHARACTERISTICS**



(57) A new type of fiber filter is useable in optical communication systems. In particular, the fiber filter may be used to flatten the gain of erbium-doped fiber amplifiers (EDFAs). Such gain flattening is important for long-haul, dense (wavelength dependent multiplexed) WDM communication systems. The filter includes a periodic mechanical structure pressed against the side of a single-mode fiber to induce a wavelength-dependent loss in a signal propagating in the fiber core by coupling the signal to fiber cladding modes. The mechanical structure is a periodic comb of small ridges. Each ridge induces a local index change in the fiber via the photoelastic effect. For coupling to the right cladding modes, the period of the grating (and the comb) is in the range of few hundreds of microns. Thus, the grating is easy to fabricate with standard machining equipment. Such filters show low loss (e.g., <0.5 dB) and exhibit the type of filter functions required to flatten the gain of an EDFA. Compared to known photosensitive long-period fiber gratings, which are currently in favor for this application, the filter is simpler and faster to fabricate. The filter does not require capital intensive UV lasers. The filter is adjustable and can be removed easily. The filter is potentially easy to mass-produce. In certain embodiments, the polarization effects caused by asymmetric application of force to polarized light are reduced or eliminated by utilizing a groove to receive the fiber. In alternative embodiments, the polarization effects are enhanced to provide an all-fiber polarizer.

**TUNABLE, MECHANICALLY INDUCED LONG-PERIOD
FIBER GRATING WITH ENHANCED POLARIZING CHARACTERISTICS**

Abstract of the Disclosure

A new type of fiber filter is useable in optical communication systems. In particular, the fiber filter may be used to flatten the gain of erbium-doped fiber amplifiers (EDFAs). Such gain flattening is important for long-haul, dense (wavelength dependent multiplexed) WDM communication systems. The filter includes a periodic mechanical structure pressed against the side of a single-mode fiber to induce a wavelength-dependent loss in a signal propagating in the fiber core by coupling the signal to fiber cladding modes. The mechanical structure is a periodic comb of small ridges. Each ridge induces a local index change in the fiber via the photoelastic effect. For coupling to the right cladding modes, the period of the grating (and the comb) is in the range of few hundreds of microns. Thus, the grating is easy to fabricate with standard machining equipment. Such filters show low loss (e.g., <0.5 dB) and exhibit the type of filter functions required to flatten the gain of an EDFA. Compared to known photosensitive long-period fiber gratings, which are currently in favor for this application, the filter is simpler and faster to fabricate. The filter does not require capital intensive UV lasers. The filter is adjustable and can be removed easily. The filter is potentially easy to mass-produce. In certain embodiments, the polarization effects caused by asymmetric application of force to polarized light are reduced or eliminated by utilizing a groove to receive the fiber. In alternative embodiments, the polarization effects are enhanced to provide an all-fiber polarizer.

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**TUNABLE, MECHANICALLY INDUCED LONG-PERIOD
FIBER GRATING WITH ENHANCED POLARIZING CHARACTERISTICS**

Background of the Invention

5 Field of the Invention

The present invention is in the field of passive filtering of optical signals in optical amplifiers, such as, for example, erbium-doped fiber amplifiers (EDFAs).

Description of the Related Art

Long period fiber gratings are described, for example, in A.M. Vengsarkar,
10 et al., *Long-Period Fiber Gratings as Band-Rejection Filters*, Journal of Lightwave Technology, Vol. 14, No. 1, January 1996, pp. 58-65. Such long-period fiber gratings are quickly becoming the filters of choice in several important communication applications. In particular, such filters are used to flatten the gain of EDFAs. The long-period fiber grating is based on the same principle and is fabricated with the
15 same technology as standard reflection fiber gratings, which were invented nearly two decades ago. In a reflection fiber grating, a spatially modulated UV laser beam is launched onto one side of a single mode fiber. Via complex mechanisms, now relatively well understood, the regions of the fiber exposed to a high UV intensity experience a refractive index change Δn in the vicinity of the core of the fiber,
20 whereas the regions of the fiber receiving a low UV intensity experience a relatively small refractive index change. Thus, the fiber core index is periodically changed by Δn with a spatial period Λ equal to the period of the spatially modulated UV beam.

To support a grating of the above-described type, the fiber must be sensitive to the UV, a property generally known as photosensitivity. The presence of sufficiently
25 strong photosensitivity to form gratings generally requires the core to be doped with germanium oxide. The photosensitivity of fibers can also be enhanced, as described, for example, in P.J. Lemaire, et al., *High pressure H₂ loading as a technique for achieving ultrahigh UV photosensitivity and thermal sensitivity in GeO₂ doped optical fibres*, Electronics Letters, Vol. 29, No. 13, June 1993, pp. 1191-1193.
30 Photosensitivity can be induced in non-Ge-doped fibers by loading the fiber with hydrogen prior to UV exposure.

In photosensitive reflection fiber gratings, the period Λ is selected such that the signal traveling in the core (the fundamental mode LP_{01}) is coupled to the LP_{01} mode traveling in the other direction. Thus, the forward-traveling signal is coupled (partially or fully, depending on the grating) to the backward-traveling signal. The grating acts as a reflector. For this reflection to take place, Λ must be fairly small. For example, Λ should be on the order of a fraction of the signal wavelength.

In the second type of photosensitive fiber gratings, the long-period grating, the forward LP_{01} signal mode is not coupled to the backward mode. Instead, the forward LP_{01} signal mode is coupled to a cladding mode. Since the cladding modes are strongly attenuated by the jacket surrounding the fiber, the LP_{01} mode is attenuated. However, if a broadband signal travels in the fiber, for a given period Λ , only certain wavelengths will be coupled to cladding modes. For other wavelengths, there may be no cladding modes to which the signals at those wavelengths can be coupled. Thus, the signals at those wavelengths experience no loss. Therefore, the grating attenuates only some wavelengths (i.e., the grating acts as a wavelength-dependent filter). To couple the LP_{01} mode to a cladding mode, the period Λ for a long-period grating must be much longer than Λ for a reflective grating. Typically, Λ for a long-period grating is on the order of tens to several hundred microns. The transmission versus wavelength of such long-period grating filters exhibits multiple attenuation notches or dips. By appropriately selecting Δn , Λ , and the grating length, the depth and (nearly periodic) location of the various dips in the filter function can be advantageously controlled.

Long-period gratings are especially important to flatten the gain of an EDFA. A standard scheme is to place a filter with a suitable filter function at some optimum location near the EDFA. It turns out that for EDFAs, the desired filter functions exhibit the kind of shape and amplitude that can easily be generated with a long-period fiber grating.

One difficulty with these exemplary long-period fiber gratings is that an expensive UV laser is required to fabricate the gratings. For example, an excimer laser having a wavelength around 248 nanometers and costing approximately \$60,000 has been utilized to fabricate such gratings. The fabrication of fiber gratings is consequently reserved to the relatively few laboratories having such equipment. A

second difficulty is that the response of a fiber to a particular UV exposure depends strongly on the chemistry, the composition and the thermal history of the fiber in ways that are too complex to model and that must be determined empirically. Thus, the fabrication process is not easily reproducible from one fiber to the next. When presented with the task of fabricating a particular long-period fiber grating filter in a particular fiber, manufacturers must go through several iterations, often based on trial and error, which adds cost and delays to the manufacturing of such filters. A third difficulty is that reproducibility requires particularly careful control of the UV laser power and fiber parameters, which can be difficult.

There are other ways of constructing long period fiber gratings. One is to arc (with an electrical arc, e.g., from a commercial fiber splicer) across the fiber, which locally releases the stress built into the fiber and locally modifies the index. The process is repeated at regular intervals, with a period Λ , along a length L of fiber. Another method is to arc and pull the fiber slightly, which deforms it a little and thus perturbs the mode index. These two methods work for any fiber without prior processing (unlike photosensitive gratings) but they are also permanent. However, a main practical difficulty that arises in the manufacturing of long period fiber gratings is that the transmission function of the fiber is difficult to control since it depends on the difference between two large numbers of comparable magnitude, namely n_{eff} and n_{cl}^m , which are the effective index of the LP_{01} core mode and the effective index of the m^{th} cladding mode, respectively. (See Equation (1) below.) Both n_{eff} and n_{cl}^m depend strongly on fiber parameters, and small variations in either or both of these indices that would have little effect in a reflection grating have a large effect on the long period fiber grating's wavelengths of peak attenuation, making it difficult to reproducibly manufacture gratings of a desired transmission.

Another kind of fiber device relevant to the present invention is a periodically stressed device, like the ones invented at Stanford University in the 1980s. (See, for example, R.C. Youngquist, et al., *Two-mode fiber modal coupler*, Optics Letters, Vol. 9, No. 5, May 1984, pp. 177-179; and R.C. Youngquist, et al., *Birefringent-fiber polarization coupler*, Optics Letters, Vol. 8, No. 12, December 1993, pp. 656-658.) When pressure is applied to a glass fiber, its core is deformed. Also, the index of the fiber changes via the photoelastic effect. The first effect has been used in a two-mode

fiber to produce a mode coupler. (See Youngquist, et al., *Two-mode fiber modal coupler*, cited above.) A two-mode fiber is a fiber in which light can propagate in one or both of two transverse modes (e.g., the LP_{01} mode and the second-order mode LP_{11}). Pressure is applied periodically along the fiber by pressing a mechanical plate against the fiber. The metal plate is made of a periodic comb of square ridges. Each ridge locally squeezes and deforms the fiber. At the beginning and at the end of each stressed region, the deformation couples a little power from the LP_{01} to the LP_{11} mode. For this effect to accumulate and to cause the transfer of substantial power between modes, the phase between coupling points must be correct. In particular, the ridge period must be substantially equal to the beat length between the two modes. For example, the device demonstrated in Youngquist, et al., *Two-mode fiber modal coupler*, cited above, had a proper period of approximately 430 microns and produced up to 40 dB coupling from the LP_{01} mode to the LP_{11} mode.

The second effect is index change with pressure. The second effect has been used to produce a polarization coupler using a high-birefringence fiber. (A high birefringence fiber is a fiber in which light can propagate in one or both of two well-defined linear polarizations.) The polarization coupler couples substantially all the power from one polarization to the other. (See, for example, Youngquist, et al., *Birefringent-fiber polarization coupler*, cited above.) For such strong coupling to take place, a mechanical plate made of a periodic comb of square ridges is pressed against the fiber. Preferably, the comb is placed at 45° to the fiber birefringent axes. Each ridge causes an asymmetric perturbation in the fiber index, which perturbs the birefringence of the fiber in the portion affected by the comb. The index perturbation allows a small amount of coupling to take place at the beginning and at the end of each stress region. Full coupling occurs when the period of the stress region is equal to the beat length between the two polarization modes. The described device has a ridge period of approximately 820 microns and yields up to 25 dB coupling of one polarization to the other. (See, Youngquist, et al., *Birefringent-fiber polarization coupler*, cited above.)

30 Summary of the Invention

As will be described in more detail below, the present invention is directed to a class of all-fiber filters that produce similar filter functions to those of

photosensitive and fused long-period fiber gratings. A filter in accordance with the present invention is simple and fast to fabricate, can be removed easily, does not require capital intensive equipment, is adjustable, and is potentially easy to mass produce. Like most all-fiber devices, a filter in accordance with the present invention
5 exhibits very low loss.

Brief Description of the Drawings

The present invention will be described below in connection with the accompanying drawing figures in which:

Figure 1 illustrates a generalized embodiment of the invention in which pressure
10 is applied periodically to a fiber to induce a periodic variation in the refractive index, thereby forming an optical grating;

Figures 2A and 2B illustrate a fiber oriented perpendicularly and obliquely to a set of ridges, respectively, so that the spatial period between pressure points along the fiber is different;

15 Figures 3A and 3B illustrate experimental systems for measuring the transmission properties of a fiber subjected to period variations in pressure using unpolarized and polarized light sources, respectively;

Figure 4 illustrates an experimentally determined transmission spectrum obtained with a mechanical grating filter;

20 Figure 5 illustrates a series of experimentally determined transmission spectra obtained with a mechanical grating filter in which increasing pressure is applied to the filter;

Figure 6 illustrates a series of experimentally determined transmission spectra for which the period of the pressure grating was varied, which shifted the transmission
25 spectra;

Figure 7 illustrates two transmission spectra for which the length of the grating fiber over which pressure is applied was different, which changed the linewidth of the attenuation notches;

Figure 8 illustrates a grooved, wedge-shaped plate in which the grating length can be varied by varying the position of the fiber;

Figure 9 illustrates a system for producing substantially polarization independent attenuation, in which two filters apply pressure to a grating fiber at 90° to each other;

5 Figure 10 illustrates a system for producing polarization independent operation in which pressure is applied to a grating fiber with radial symmetry;

Figure 11 illustrates an exemplary cross section of the embodiment of Figure 1 showing that the ridges which make contact with the fiber are generally flat to avoid microbends in the fiber;

10 Figures 12A and 12B illustrate another radially symmetric filter embodiment similar to that of Figure 10;

Figure 13 is a measurement illustrating how attenuation through a fiber grating is a function of polarization;

15 Figures 14 and 15 illustrate perspective and cross-sectional views, respectively, of an embodiment for reducing the polarization dependence of a fiber's attenuation, in which the fiber resides within a V-shaped groove;

Figures 16 and 17 illustrate another embodiment for reducing the polarization dependence of a fiber's attenuation, in which the fiber resides between two V-shaped grooves;

20 Figure 18 illustrates an embodiment, which includes several grooves, with each groove having its own periodicity;

25 Figures 19 and 20 illustrate plan and cross-sectional views, respectively, of an embodiment in which a fiber experiences pressure points which are spaced aperiodically from each other to produce a broadened fiber polarizer, with the pressure points being located along ridges spaced periodically from each other;

Figures 21 and 22 illustrate plan and cross-sectional views, respectively, of an alternative embodiment in which a fiber experiences pressure points which are spaced aperiodically from each other to produce a broadened fiber polarizer, with the pressure points being located along ridges spaced aperiodically from each other;

Figures 23 and 24 illustrate plan views of chirped grating embodiments utilizing polarization maintaining fiber in which the ridges are spaced periodically and aperiodically from each other, respectively;

Figures 25 and 26 illustrate an embodiment designed for polarization maintaining fiber, which increases the separation between attenuation peaks corresponding to different polarizations; and

Figures 27A and 27B illustrate optical waveguide embodiments which function as optical polarizers.

Detailed Description of the Preferred Embodiment

The basic principle of a filter 100 in accordance with the present invention will be explained first in connection with Figure 1. Rather than using the photosensitive effect or arcing of the fiber, the filter 100 induces a periodic perturbation of the refractive index Δn of a fiber 110 by applying periodic pressure to the surface of the fiber 110. For example, the periodic pressure is applied by squeezing the fiber 110 between a first plate 112 and a second plate 114. A spring-loaded clamp (not shown) may be advantageously used to provide the pressure.

The second plate 114 has a plurality of ridges 116 formed thereon to form a ridged comb having a length L and a period Λ . Alternatively, both the first plate 112 and the second plate 114 may each have ridges therein, as shown by the ridges 116 shown in phantom in Figure 1. The ridges 116 are advantageously formed by cutting grooves in the surface of a flat plate. Other techniques, such as chemical etching, ion etching, or micromachining, can also be used, in any number of materials such as metals, glasses, crystals, polymers, etc. For example, the grooves in a preferred embodiment have a depth of approximately 125 microns. The ridges 116 are pushed against the fiber 110 to produce a plurality of alternating stressed areas 118 and unstressed areas 120 in the fiber 110. The core and the cladding of the fiber 110 in the stressed areas 118 experience a change in refractive index, while the core and cladding in the unstressed areas 120 do not. This change in the refractive index is believed to be due at least in part to the photoelastic effect. Hence, a periodic grating is formed in the fiber 110. To act as a wavelength-dependent filter, the device 100 must (1) attenuate a particular subset of wavelengths, and (2) be highly transmissive

at the remaining wavelengths. The period Λ of the stressed regions 118 must thus be such that at the first subset of wavelengths, the period is equal to the beat length between the LP_{01} mode and a cladding mode of the fiber 110. Also, to meet the second condition at the remaining wavelengths, the fiber 110 must support no
 5 cladding modes to which the LP_{01} mode can be coupled.

In the filter 100, the grating period is controlled by the period Λ of the ridged comb 114 along the longitudinal axis of the fiber 110. The proper period Λ depends on the propagation characteristics of the LP_{01} and cladding modes of the fiber 110. The propagation characteristics depend on the core and cladding index profiles of the
 10 fiber 110. However, the period Λ can be as large as several hundred microns. This relatively large value for the period Λ makes it easy to fabricate such combs with standard machining equipment by forming grooves in a plate of metal or the like. The material remaining between the grooves forms the ridges 114. If a shorter period were required (i.e., to produce reflection gratings), the task would be more difficult,
 15 but possible, using, for example, micromachining or etching.

The foregoing can be understood mathematically as follows. As discussed above, the grooved plate 114 has a ridge periodicity Λ and is pressed against a length L of the fiber 110 to induce a periodic index change along the fiber 110 via the photoelastic effect. As discussed in V. Bhatia, et al., *Temperature-Insensitive and*
 20 *Strain-Insensitive Long-Period Grating Sensors for Smart Structures*, Optical Engineering, Vol. 36, No. 7, July 1997, pp. 1872-1876, when the spatial index in a photoinduced long-period fiber grating has a period in the right range (e.g., tens to hundreds of microns), there are distinct optical wavelengths λ_m at which power traveling in the fundamental LP_{01} mode of the core is coupled to forward-propagating
 25 cladding modes of order m . The coupling also occurs for like reasons for the mechanically induced long-period fiber grating of the present invention. The phase matching condition that must be met by wavelengths λ_m can be written as:

$$\lambda_m = (n_{eff} - n_{cl}^m) \Lambda \quad (1)$$

where n_{eff} is the effective index of the LP_{01} core mode and n_{cl}^m that of the m^{th}
 30 cladding mode, both evaluated at wavelength λ_m . In general, for a particular period Λ , several cladding modes satisfy this condition, each one at a different center

wavelength λ_m that increases with the order of the mode. The filter transmission spectrum thus exhibits a series of attenuation notches distributed over a spectral range of a few hundred nanometers. (See, for example, the spectra illustrated in A.M. Vengsarkar, et al., *Long-Period Fiber Gratings as Band-Rejection Filters*, cited above; and V. Bhatia, et al., *Temperature-Insensitive and Strain-Insensitive Long-Period Grating Sensors for Smart Structures*, cited above.). As implied by Equation 1, the positions of the attenuation notches depend on the core and cladding index profiles, which determine n_{eff} and n_{cl}^m , respectively. Because the difference $n_{eff} - n_{cl}^m$ is small when coupling to lower order cladding modes, the period Λ can be a large fraction of a millimeter, which can be conveniently achieved by mechanical means.

The spectral power transmission $T(\lambda)$ of the filter notch arising from coupling to the m^{th} cladding mode is given by the approximation developed in A.M. Vengsarkar, et al., *Long-Period Fiber Gratings as Band-Rejection Filters*, cited above:

$$T(\lambda) = 1 - \frac{\sin^2 \left[\kappa_m L \sqrt{1 + \left(\frac{\delta_m}{\kappa_m} \right)^2} \right]}{1 + \left(\frac{\delta_m}{\kappa_m} \right)^2} \quad (2)$$

where δ_m is the detuning parameter $\delta_m = \pi \left[(n_{eff} - n_{cl}^m) / \lambda - 1 / \Lambda \right]$ and κ_m is the grating coupling constant, in which both quantities are evaluated for mode m . The coupling constant κ_m scales like the pressure-induced index change Δn , and it controls the depth of the notches.

Assuming complete transfer (i.e., $\kappa_m L = \pi/2$), an approximate expression for the full width half maximum (FWHM) $\Delta\lambda_m$ of a notch is:

$$\Delta\lambda_m = \frac{0.8\lambda_m^2}{L(n_{eff} - n_{cl}^m)} \quad (3)$$

Equation 3 shows that increasing the length over which the perturbation is applied results in narrower notch linewidths. For a filter designed to operate in a given wavelength range, e.g., $\lambda_m \cong 1.5$ -1.6 microns, equation 3 shows that $\Delta\lambda_m$ is primarily

determined by the product $L(n_{eff} - n_{cl}^m)$. In general, it is advantageous to design the filter such that the length of fiber L that is required is relatively short, e.g., $L \lesssim 5$ cm. To accomplish this, equation 3 shows that it is advantageous to have a fiber designed such that the difference $(n_{eff} - n_{cl}^m)$ is as large as possible in practice. This in turn
 5 means that the fiber should have a guided mode LP_{01} that is reasonably far from cutoff, which will guarantee that n_{eff} is substantially larger than n_{cl}^m .

The filter 100 is substantially different from the two-mode coupler discussed above, in which it is the periodic external fiber deformation that causes coupling. In the polarization coupler, coupling is caused by a periodic change in index, as in the
 10 present invention, but coupling occurs between polarization modes, not between the LP_{01} mode and cladding modes. Thus, the wavelength dependence of the polarization coupler is likely to be substantially different than the wavelength dependence of the filter 100 of the present invention. Since the wavelength dependence is the property that produces the desired filter function, the coupling between the polarization modes
 15 would not likely produce the desired filter function.

The pressure applied to the plate 114 controls the magnitude of Δn . Thus, the amount of power coupled per unit length and the attenuation of the filter are controlled in part by the pressure. The attenuation is also controlled by the length of the plate 114 under pressure. The length of the plate 114 also controls the linewidth
 20 of the attenuated wavelengths of the filter 100. The ridge sequence can also be constructed to be aperiodic to generate more complex filter functions, as discussed below.

In the filter 100, the filter function is effective as long as the pressure continues to be applied to the plate 114. The filter function disappears when the
 25 pressure is removed. The filter 100 can thus be applied and removed many times without damaging the fiber 110.

The filter function is also adjustable. One method of adjustment is to release the pressure, rotate the plate 114 by a selected angle about its mid-point, and press the plate 114 against the fiber 110 again. The fiber 110 then sees a different (longer)
 30 period equal to the comb period Λ divided by the cosine of the angle by which the plate 114 was rotated. This is illustrated in Figure 2A, which illustrates the fiber 110

oriented perpendicular to the ridges 116 corresponding to for a first period $\Lambda_1 = \Lambda$ and in Figure 2B, which illustrates the fiber 110 oriented at a different angle to the ridges 114 to provide a second period $\Lambda_2 = \Lambda / \cos \theta$ along the length of the fiber 110. As illustrated, the period Λ_2 is longer than the period Λ_1 .

5 Figure 3A illustrates an experimental system 200 in which broadband optical radiation such as white light from a source 310 is applied to the device 100 of Figure 1. For the purpose of the experiment, the light first propagates through a filter 100 constructed in accordance with the filter 100 of Figure 1. After propagating through the filter 100, the light is output to an optical spectrum analyzer 240. In one particular
10 embodiment, the optical fiber 110 is a Corning SMF-28 CPC single-mode fiber having a core diameter of 8.3 microns, a cladding diameter of 125 microns, and a core refractive index difference of 0.3%. Figure 3B illustrates an experimental system 202 in which a polarized laser source 311 is applied to the device 100 of Figure 1. The light first propagates through a polarization controller 314 and then through a filter
15 100 constructed in accordance with the filter 100 of Figure 1, before it is output to an optical spectrum analyzer 240. All of the experimental data presented herein were obtained with the experimental setup of Figure 3A, except for the data of Figure 13 which were obtained with the setup of Figure 3B.

Figure 4 illustrates an exemplary transmission spectrum 350 of the mechanical
20 grating filter 100, measured with the setup of Figure 3A, when Λ is selected to be 580 microns and pressure is applied over a length L of 2.5 centimeters. As illustrated for light in the range of 1,400 to 1,600 nanometers, the transmission spectrum 350 includes three attenuation notches 352, 354, 356 at approximately 1,420 nanometers, 1,455 nanometers and 1,525 nanometers, respectively, which correspond to coupling
25 from the core to one of the first three cladding modes.

Figure 5 illustrates an exemplary transmission spectrum 400 of the filter 100 for a period Λ of 712 microns and for light in the range of 1,520 nanometers to 1,660 nanometers, again measured with the setup of Figure 3A. The period of 712 microns is advantageously obtained by positioning the fiber 110 at an angle with respect to the
30 plate 114 of Figure 1 to increase the period. Figure 5 includes a plurality of curves 410, 420, 430, 440, 450, which represent measurements for different increasing pressures applied to the filter 100. The first curve 410 illustrates relatively low

attenuation resulting from relatively low pressure applied to the filter 100. The second curve 420, the third curve 430, the fourth curve 440 and the fifth curve 450 illustrate the results of increasing the pressure applied to the filter 100.

From the curve 420 to the curve 440, the increasing pressure results in larger coupling constants κ_m and deeper notches. For this grating length and for this range of pressure, the increasing pressure increases the amount of optical power coupled from the core mode to the cladding mode and thus the amount of power lost from the core of the fiber 110. However, if the applied pressure is increased beyond a certain point, one expects that the notch depth will reach a maximum, then decrease. This behavior is supported by Equation 2 over certain ranges of grating length L and coupling constant κ_m . This is what is observed in Figure 5 for the leftmost notch (at 1565 nm): When the pressure is increased from the curve 440 to the curve 450, the attenuation of that notch decreases, while the attenuation of the rightmost notch (at 1615 nm), which has not reached its maximum, continues to increase.

As illustrated in Figure 5, the transmission spectrum 400 includes two distinct transmission notches (i.e., attenuation peaks) for each of the curves 410, 420, 430, 440, 450. The leftmost peak (shorter wavelength) of each curve (e.g., a peak 460 for the curve 450) at approximately 1,565 nanometers represents the coupling of light from the core to the lowest order cladding mode. The rightmost peak (longer wavelength) of each curve (e.g., a peak 470 for the curve 450) at approximately 1,615 nanometers represents the coupling of light from the core to the next order symmetric cladding mode. Note that attenuation in excess of 14 dB (transmission less than -14 dB) can be obtained. For all cases, the out-of-band attenuation, for example, at 1,540 nanometers, is less than 0.5 dB. Thus, the residual loss in the fiber 100 is very low. It has been found that the residual attenuation loss can be maintained at a lower value than shown in Figure 5 by keeping the fiber under slight tension before clamping it between the plate 112 and the plate 114 (a step which was not taken when measuring Figure 5). It is believed that this causes stiffening of the fiber 110, which reduces the microbending.

The filter 100 illustrated in Figures 1-3A,B has three parameters which can be adjusted independently, and each of the adjustable parameters affects a respective different parameter of the filter spectrum illustrated in Figure 5. The first adjustable

parameter is the period Λ , which can be used to adjust the locations of the peaks (e.g., peaks 460, 470 of the filter spectrum 400). The parameter Λ can be adjusted by varying the period of the ridges 116 in the plate 114 or by adjusting the orientation of the fiber 110 with respect to the ridges, as illustrated in Figures 2A and 2B. The effects of adjusting the period of the ridges 116 is illustrated by the set of curves 500 in Figure 6, which represents the transmission spectra for gratings having periods ranging from 683 microns to 722 microns and having a length of approximately 2.5 centimeters. A first curve 510 represents the filter function for a grating having a period of 683 microns. A second curve 512 represents the filter function for a grating having a period of 703 microns. A third curve 514 represents the filter function for a grating having a period of 712 microns. A fourth curve 516 represents the filter function for a grating having a period of 722 microns. As illustrated, a longer grating period shifts the attenuation peaks towards longer optical wavelengths. For example, the leftmost (lower wavelength) peak for the 683-micron grating occurs at approximately 1,535 nanometers. In contrast, the leftmost peak for the 722-micron grating occurs at approximately 1,585 nanometers. By comparing the location of the leftmost lobes of Figure 4 for a grating period of approximately 580 microns and the location of the leftmost lobe of Figure 5 for a grating period of 722 microns, it can be seen that the attenuation can be tuned over a range of at least 165 nanometers, from approximately 1,420 nanometers to approximately 1,585 nanometers. (Larger ranges are possible by further increasing the angle between the fiber and the grating.)

The second adjustable parameter is the length of the region under pressure. By adjusting the length of the region under pressure, the widths of the peaks of the filter function can be adjusted, as predicted by Equation 3. The effect of the length of the squeezed region on the linewidth of the filter function is illustrated in Figure 7 for two different lengths. A first curve 610 represents the filter function for a grating having a length of 1.9 centimeters. A second curve 620 represents the filter function for a grating having a length of 2.5 centimeters. Note that the linewidths of the transmission notches (attenuation peaks) for the curve 610 are wider than the linewidths of the transmission notches for the curve 620. The linewidths of the transmission notches (defined as the full width at half maximum (FWHM)) are approximately proportional to the inverse of the respective fiber grating length.

Experimentally, the linewidths have been observed to be in the range of 5-25 nanometers. In an experimental setup, the grating length can be varied by providing a wedge-shaped plate 650 having substantially parallel rows of grooves 652 therein (which define rows of ridges between the grooves for contacting a fiber), as illustrated in Figure 8. By positioning the fiber in different locations on the plate 650, the grating length can be varied without changing the periodicity of the pressure points experienced by the fiber. For example, a first fiber position 660 and a second fiber position 670 are illustrated in Figure 8. Once again, a top plate (not shown) can be used for compressing the fiber onto the plate 650.

The third adjustable parameter is the amount of pressure applied to the plate. The amount of pressure controls the depths of the transmission notches, as was discussed above in connection with Figure 5. As illustrated, although the depths of the perturbation notches generally increase with increasing pressure (up to some pressure), the shapes of the notches remain substantially the same. In particular, the notches can be described as a sinc^2 function (i.e., a $(\sin x/x)^2$ function).

All results presented so far involved an unpolarized (white light) source. However, in the form described so far, the filter function provided by the filter 100 is polarization dependent because the index change is different in the direction of the applied pressure from the direction orthogonal to it. To test the polarization dependence of a mechanically induced long-period fiber grating, a polarized tunable laser was used as a light source. The polarization controller 314 (see Figure 3B) was placed between the source and the long-period fiber grating filter. The polarization of the input signal was changed with the polarization controller 314 until the filter produced a minimum transmission. The polarization was again adjusted until the filter produced a maximum transmission. These measurements were then repeated for a series of wavelengths across the filter attenuation notch.

The results of the foregoing measurements are plotted in Figure 13 as a first spectrum 950 for a first polarization and a second spectrum 952 for a second polarization. The spectra 950, 952 show significant polarization dependence. The attenuation peak 960 for the first spectrum 950 occurs at a wavelength that is approximately 4 nanometers from the attenuation peak 962 for the second spectrum 952. The peak attenuations 960, 962 differ by approximately 2.3 dB. Figure 13 also

illustrates an unpolarized filter spectrum 970, measured with the same filter but with an unpolarized white light source, and also illustrates an average 980 of the two polarized spectra (dotted line), which agrees well with the unpolarized filter spectrum.

This polarization dependence can be beneficial in several applications, as discussed below. For example, the polarization dependence may be used to produce a polarized fiber laser. On the other hand, polarization dependence may be undesirable in other applications such as, for example, gain flattening. The polarization can be greatly reduced by a number of methods.

A first method of obtaining substantially polarization independent operation is illustrated in Figure 9, which is similar to Figure 3A described above. Two polarization controllers 314 and 330 are used, and two filters 810, 820 are positioned on the same (low-birefringent or high-birefringent) fiber 830, one after the other and fairly close to each other. The pressure applied to the fiber 830 by the second filter 820 is oriented at 90° with respect to the pressure applied by the first filter 810, thus effectively causing equal pressure to be applied to each of the polarization axes of the fiber 830.

A second method of reducing the polarization dependence is to apply the pressure to a fiber 850 with a cylinder 860, as illustrated in Figure 10. The cylinder 860 has ridges 870 on its inner surface. The inner diameter (ridge crest to ridge crest) defined by the curved end surfaces of the ridges 870 is slightly smaller than the outer diameter of the fiber 850 (see cutaway portion of Figure 10). The inner ridges 870 have the same period as described earlier. The cylinder 860 is divided lengthwise in two halves 880, 882, as shown in Figure 10. The two halves 880, 882 are clamped together by known mechanical clamping devices so that the two halves 880, 882 apply radially symmetric pressure to the fiber 850. The index change is then polarization independent.

In any of the embodiments described thus far, it is advantageous to avoid inducing microbends in the fiber where the corners of the ridges contact the fiber. Such microbends induce losses at all wavelengths. To avoid the microbends, the corners of the ridges should not be too sharp. Sharp corners can be avoided by one of many techniques, including mechanical abrasion, polishing, etching, ion milling, etc., depending on the material used. Figure 11 illustrates an exemplary cross section of

the second plate 114 of Figure 1. As illustrated, the ridges 116 between the grooves have generally flat tops to enhance the contact with the fiber 110 and to reduce microbending of the fiber.

As stated above, the filter function persists only as long as the pressure is on. As illustrated in Figures 12A and 12B, a permanent filter 900 can be advantageously formed on a fiber 910 by using a cylinder 920 having internal ridges such as ridges 870 in Figure 10. However, in Figures 12A and 12B, the cylinder 920 is not split in two halves. Rather, the cylinder 920 is a single-piece filter. The inner diameter of the cylinder 920 is again selected to be slightly smaller than the outer diameter of the fiber 910. The cylinder 920 advantageously comprises a material with a high thermal expansion coefficient compared to silica. For example, the cylinder 920 may be fabricated from a metal. The cylinder 920 is first heated to cause the cylinder 920 to expand, thereby causing its inner diameter to become larger than the outer diameter of the fiber 910. Thus, the fiber 910 can be slipped through the cylinder 920 between the ridges, as illustrated in Figure 12A. Upon cooling, the cylinder 920 shrinks around the fiber 910 and becomes effectively sealed against the fiber 910, thus applying a constant pressure to the fiber 910, as illustrated in Figure 12B. This approach may prohibit the use of a fiber jacket with a low melting point, but can be used with fiber coatings such as amorphous carbon or metals.

In the alternative, rather than heating the cylinder 920, the fiber 910 is cooled to a cryogenic temperature so that the fiber 910 shrinks to a sufficiently small diameter that it may be readily slipped into the cylinder 920. Then, as the fiber 910 returns to ambient temperature, the fiber 910 expands so the inner ridges of the cylinder 920 apply pressure to the fiber 910. This method would not jeopardize the mechanical integrity of the fiber jacket.

As a further alternative, a combination of heating the cylinder 920 and shrinking the fiber 910 may advantageously be used. Such methods are commonly used in mechanical engineering to lock metal parts together. Regardless of which of the three methods is used, the maximum or minimum temperature of the fiber 910 must be sufficiently modest to avoid physical damage or breaking of the fiber 910 or alteration of the properties of the fiber core, such as by dopant diffusion or the like.

A possible difficulty is that the pressure applied by the plate or cylinder to the fiber is likely to be affected by the external temperature, because the two materials expand at different rates. Thus, as the external temperature varies, the fiber and the stress member expand differently, the applied stress varies, and the filter function changes. This effect is slow but is undesirable in general. The effect may be reduced in the above-described permanent fixture (i.e., in the embodiment utilizing the cylinder). Another way to reduce variation in applied stress is to utilize a stress member comprising a material having a thermal expansion coefficient matched to that of the fiber.

An alternative implementation of the present invention involves lightly melting or softening the fiber on a spatially periodic pattern (instead of stressing it externally). The heat is expected (1) to cause some compaction of the fiber, and (2) to induce permanent stresses in the heated regions. Both effects are known to induce changes in the local refractive index. Two methods may be used to induce a permanent thermal index grating. In the first method, a segment of fiber is exposed to the focused beam of a laser with a wavelength that is absorbed by the fiber material, e.g., a 10.6-micron CO₂ laser for a silica-based fiber. The laser beam is focused to the right diameter (roughly half a period of the final grating). The heat deposited by the laser must not migrate (via conduction) too far into the rest of the fiber on either side of the laser-irradiated segment (otherwise these areas will melt or soften too). To this end, the laser is pulsed, and the pulses are sufficiently short that during a given pulse the heat deposited in the fiber does not have time to be conducted into the surroundings. The time it takes heat to diffuse out of the fiber is typically on the order of hundreds of milliseconds to seconds, so that a laser delivering sub-millisecond pulses may be advantageously used. After the delivery of a pulse, heat diffuses along the fiber on both sides of the exposed region so that the region perturbed by the heat is longer than the laser beam diameter. This effect can be corrected by using a beam diameter narrower than a half period by a prescribed amount. The prescribed amount is determined by modeling or is determined empirically. A grating is formed by displacing either the laser or the fiber (or by displacing both) by half a period and repeating this process until the desired length has been processed. Other configurations are possible. For example, as is done with photosensitive fiber

gratings, the fiber can be exposed to a laser interference pattern with the correct period corresponding to the desired grating. The interference pattern can be produced advantageously by interfering two laser beams split from the same laser so as to generate a spatially modulated pattern with the required period. The desired pattern
5 can also be produced with a phase mask of suitable period.

In a further implementation of the present invention, the fiber core (or a larger transverse section of the fiber) contains a dopant that absorbs strongly over a wavelength range away from the signal wavelength window. For example, the dopant absorbs only below 700 nanometers, so that a signal at 1.3 or 1.55 microns propagates
10 through the fiber without dopant-induced loss. The grating is formed by exposing the fiber to a laser having a wavelength which is absorbed by the dopant. The laser is applied either point by point or with an interference pattern, as described above. The laser is pulsed. If only the core is doped, the pulses must be shorter than the time it takes heat to be conducted out of the core, which is typically approximately 5-25
15 microseconds, depending on the fiber core size. If a transverse region larger than the core is doped and exposed to laser light, the pulses need to be shorter than the time it takes heat to be conducted out of that region. The conduction time is longer than approximately 5-25 microseconds, depending on the transverse size of the exposed region. Thus, the pulses need to be shorter than this conduction time. The described
20 method offers the benefit of possibly using a wider range of lasers by proper selection of the dopant or dopant combinations.

In photoinduced long-period fiber gratings, the transmission function is affected by external temperature variations mainly through the temperature dependence of the difference between the effective index of the LP₀₁ and that of the
25 cladding mode. Similar effects are expected in a mechanically induced long-period fiber grating in accordance with the present invention. A smaller contribution is also expected from variations in the period Λ via thermal expansion of the grooved plate 114. These mechanisms lead to a temperature dependence of the peak wavelength.

The peak of attenuation of the notches may also depend on temperature, in
30 particular via the temperature dependence of the pressure exerted by the springs or other mechanism used to apply pressure to the plate 114 and thus to the fiber 110. The variations with temperature of the transmission spectrum of a mechanically

induced long-period fiber grating with a 640-micron period were measured by placing the entire mechanical fixture of Figure 1 in a water bath and slowly changing the temperature of the bath by approximately 60° C. These tests were run with two types of pressure plate 114, namely a stainless steel pressure plate and a plate of fused silica (which has a much lower thermal expansion coefficient than stainless steel) with grooves machined into the silica. The results are summarized in Table 1. For both materials, the thermal variations in the peak wavelength are small and are around 0.05 nanometers per °C. This thermal variation is comparable to the values reported for other types of long-period fiber grating filters around 1.55 μm, including photoinduced gratings. (See Table 1, and also see A.M. Vengsarkar, et al., *Long-Period Fiber Gratings as Band-Rejection Filters*, cited above.) The thermal variations are also comparable to variations in gratings fabricated by residual stress relaxation (0.037-0.070 nanometers per °C), as described, for example, in T. Enomono, et al., *Long-Period Fiber Grating in a Pure-Silica-Core Fiber Written by Residual Stress Relaxation*, Proceedings of Optical Communication Conference OFC'98, 1998 OSA Technical Digest Series Vol. 2, February 1998, pp. 277-278. With either the stainless steel plate or the glass plate, the thermal variations in the peak attenuation are around 0.04 dB/°C (see Table 1), which is relatively small but larger than for a photoinduced long-period fiber grating by a factor of approximately 4.

To verify that this larger dependence is due primarily to the temperature dependence of the pressure applied by the springs, tests were conducted with a temperature-independent pressure source. Specifically, a weight was placed on the plate 112 instead of using springs between the plates 112 and 114. Table 1 shows that the peak attenuation variation with temperature is then considerably lower, around 0.007 dB/°C. This is slightly better than reported in photoinduced long-period fiber gratings. Thus, the temperature dependence of the peak attenuation observed in the spring-loaded filters is mostly due to the temperature dependence of the spring coefficient. With a suitable, constant-force design, the dependence due to the spring coefficient can be largely eliminated, thereby making the temperature sensitivity of mechanically induced long-period fiber gratings as low as photoinduced long-period fiber gratings (LPFGs).

Table 1

Filter type	Peak wavelength	Peak wavelength shift	Peak attenuation variation
Glass grooves (spring)	1530 nm	0.048 nm/°C	0.032 dB/ °C
Metal grooves (spring)	1555 nm	0.058 nm/°C	0.048 dB/ °C
Metal grooves (weight)	1550 nm	0.047 nm/°C	0.007 dB/ °C
Photoinduced	1550 nm	0.04-0.05 nm/ °C	0.01 dB/ °C

Measured temperature dependence of the peak wavelength and peak attenuation of a mechanically induced LPFG and comparison to photoinduced LPFG.

The main reason for the temperature sensitivity of long-period fiber gratings is that the core mode and the cladding mode (to which the core mode is coupled) both have mode indices that exhibit different temperature dependencies. Thus, in Equation 1, the mean wavelength of the filter notches, which is proportional to the difference between these two indices, varies with temperature. As described in U.S. Patent 5,703,978 to DiGiovanni, et al., "Temperature insensitive long-period fiber grating devices," which is hereby incorporated by reference herein, one can reduce this dependence dramatically by selecting an index profile for the cladding such that the cladding mode and the core mode have substantially identical mode indices. This can be accomplished by using a composite cladding made of layers of different materials with different index thermal coefficients dn/dT , such that the average index seen by the cladding mode gives the cladding mode the right mode index dependence with temperature. Suitable materials include silica-based glass doped with various concentrations of phosphorus, fluorine, germanium, or other dopants. Thus, by appropriate selection of the cladding's index profile, the various embodiments of this invention can be made substantially temperature insensitive.

Figures 14 and 15 illustrate a further system 1000 for reducing polarization dependence. In particular, as illustrated in Figure 14, a lower plate 1010 has a plurality of grooves 1012 formed on a first surface to provide a plurality of alternating ridges 1014 between the grooves. The ridges 1014 have a periodicity of Λ . Unlike

the previously described embodiments, the ridged plate 1010 has a generally V-shaped groove 1020 formed in the ridges 1014 and oriented substantially perpendicular to the ridges 1014. An optical fiber 1024 is positioned in the groove 1020 so that the optical fiber 1024 is also oriented substantially perpendicular to the ridges 1014. An upper plate 1030 presses down on the optical fiber 1024, as described above. In the embodiment illustrated in Figures 14 and 15, the circumference of the fiber 1024 engages the surfaces of ridges 1014 formed by the groove 1020. Thus, rather than the fiber 1024 contacting the ridges 1014 at locations diametrically opposed to the contact with the upper plate 1030, the fiber 1024 contacts each ridge 1014 at two locations. Each contact surface of each of the ridges 1014 applies pressure to the fiber 1024 and has a vertical vector component (which opposes the pressure of the upper plate 1030 in the vertical direction) and a horizontal vector component (which applies pressure to the fiber 1024 in a horizontal direction orthogonal to the applied pressure from the upper plate 1030). Thus, in the embodiment of Figures 14 and 15, pressure is applied to the fiber 1024 symmetrically, so that the indices of refraction of the fiber 1024 are changed by similar or identical amounts, which reduces or eliminates the polarization dependence.

The angle of the groove 1020 that yields equal forces in the parallel and perpendicular directions is 60° , as shown in Figure 15, corresponding to the fiber 1024 being pressed at three points located at 120° from each other around the perimeter of the fiber. Although this is not truly azimuthally symmetric, calculations for a more general configuration in which pressure is applied to the fiber 1024 at p points symmetrically located around the fiber perimeter (e.g., every 120° for $p=3$, every 90° for $p=4$, etc.) show that for $p \geq 3$, the pressure at the center of the fiber will be symmetric, i.e., purely radial, and the filter should be fairly independent of polarization. However, these calculations assume that the pressure is applied along the entire length of the fiber 1024, i.e., they ignore the fact that the pressure is applied periodically. Nevertheless, the conclusion should still apply in the case of periodically applied pressure. Thus, to reduce or remove the polarization sensitivity of the filter, pressure is preferably applied symmetrically. For example, a 60° groove pushed against a flat plate will work (as shown schematically in Figures 14 and 15), as will a 90° groove pushed against another 90° groove (see Figures 16 and 17).

Figures 16 and 17 illustrate a further system 1050 in which a ridged lower plate 1060 has a groove 1062 formed therein as in Figures 14 and 15. In Figures 16 and 17, an upper plate 1070 also has a groove 1072 formed in it. The groove 1072 is parallel to the groove 1062 so that a fiber 1080 can rest in the two grooves 1062, 1072 between the two plates 1060, 1070. In this embodiment, the angle of the groove 1062 and the angle of the groove 1072 should be selected so that the distribution of the pressure applied to the fiber is such that the applied index perturbation is as azimuthally symmetric as possible. Although several combinations of angles are possible, a preferred embodiment involves using an angle of 90° for both the angle of the groove 1062 and the angle of the groove 1072. With this arrangement, when pressure is applied to the two plates 1060, 1070, the fiber 1080 is squeezed between the upper plate 1070 and the lower plate 1060, and the fiber 1080 has pressure applied to it at four substantially orthogonal locations at each ridge 1082 of the lower plate 1060. The embodiment of Figures 16 and 17 thus further equalizes the index changes to reduce or eliminate the polarization dependency.

Because the grooves of the embodiments of Figures 14-17 fix the orientation of the optical fibers 1024 and 1080 with respect to the ridges of the respective lower plates 1010, 1060, the angle of each fiber with respect to the ridges cannot be readily adjusted. Figure 18 illustrates an exemplary lower plate 2000 which provides an adjustable periodicity. In particular, the plate 2000 includes a plurality of ridges 2010 formed as discussed above. The plate 2000 further includes a first V-shaped groove 2020 which is oriented at a first angle orthogonal (i.e., perpendicular) to the ridges 2010. The plate 2000 further includes a second V-shaped groove 2022 which is oriented at a second, non-orthogonal angle to the ridges 2010 which causes the second groove 2022 to have an angle θ_2 with respect to a line orthogonal to the ridges 2010. The lower plate includes a third V-shaped groove 2024 which is oriented at a third non-orthogonal angle to the ridges 2010 which causes the third groove 2024 to be oriented at a second angle θ_3 with respect to a line perpendicular to the ridges 2010. Additional grooves at other different angles can also be formed in the lower plate 2000. Each of the grooves 2020, 2022, 2024 provides a different periodicity in accordance with the angle of orientation of the groove with respect to the ridges 2010.

Figures 19 and 20 illustrate a further embodiment of the present invention in which a lower plate 2100 is formed with ridges 2110 as before. Unlike the previous embodiments, a groove 2120 is formed in the lower plate 2100 as a curve which intersects the ridges 2110 at differing angles. Thus, a fiber 2130 positioned in the groove 2120 and pressed between the lower plate 2100 and an upper plate 2140 will not experience a constant periodicity, which causes the linewidths of the attenuation to broaden. Thus, the embodiment of Figures 19 and 20 will operate as a chirped grating.

Figures 21 and 22 illustrate an alternative embodiment of the chirped grating in which a lower plate 2200 has a plurality of ridges 2210 formed in it. Unlike the previous embodiments, the ridges 2210 are not evenly spaced, but instead have a varying periodicity from a first period Λ_1 to a second period Λ_2 . By varying the period Λ over a limited range, the linewidth of the transmission notches of the filter is broadened. Although the embodiment of Figures 21 and 22 can be used with or without a groove, a groove 2220 is shown. A fiber 2230 is squeezed between the lower plate 2200 and an upper plate 2240.

Chirped grating embodiments may also be constructed utilizing ridges instead of the grooves 2120 and 2220 shown in Figures 19-22. In Figure 23, for example, periodically spaced ridges 116 (like those shown in Figure 2) in the plate 114 contact the fiber 110 so that the fiber intersects the ridges 116 at differing angles. When the fiber 110 is squeezed between the plate 114 and another plate 112 (see, for example, Figure 1), pressure is applied to the fiber in such a way that the linewidths of the attenuation broaden. Likewise, Figure 24 shows an embodiment which functions like the one of Figure 23, in which the ridges 116 are unevenly spaced from each other (see, for example, Figure 21); the ridges 116 are compressed between the two plates 112 and 114 to produce a polarization sensitive, chirped filter grating.

Unlike the embodiments shown in Figures 19-22, the embodiments of Figures 23 and 24 act as polarizers. The effect of the aperiodic pressure points on the fiber 110 in Figures 23 and 24 is to produce polarizers that operate over a broad wavelength range. This is to be contrasted with the chirped, polarization-independent spectral filter embodiments disclosed herein; these polarization-independent embodiments can be used to produce a variety of spectral filter shapes, with the filter

shape being controlled, for example, by adjusting the chirped grating length or adjusting the curvature of the fiber between its plates.

The polarization-independent embodiments herein can be used to produce a variety of spectral filter shapes, with the filter shape being controlled, for example, by
5 adjusting the chirped grating length or adjusting the curvature of the fiber between its plates.

As illustrated above in connection with Figure 13, the long-period fiber grating filter in accordance with the present invention displays a significant polarization dependence using single-mode optical fiber. The two peaks 960, 962 in
10 the attenuation are approximately 4 nanometers apart. Furthermore, as illustrated for the peak 962 of the second polarization at approximately 1,525 nanometers, light propagating in the first polarization incurs approximately 4.5 dB of attenuation, while light propagating in the second polarization incurs approximately 14 dB of attenuation at this wavelength. Similarly, at the peak of the first polarization at approximately
15 1,528.5 nanometers, light propagating in the first polarization incurs approximately 12 dB of attenuation while light propagating in the second polarization incurs only approximately 4.5 dB of attenuation at this wavelength. Although the differences in attenuation are significant, the less attenuated light incurs substantial attenuation in each case which is undesirable if this filter is used as a polarizer. Thus, it would be
20 desirable to separate the attenuation peaks so that the peak attenuation for one polarization occurs at a wavelength where the other polarization incurs little, if any, attenuation. This is accomplished in accordance with another aspect of the present invention by using a polarization-maintaining fiber in place of the low birefringence fiber previously described. In particular, as illustrated by the system 2300 in Figures
25 25 and 26, a polarization-maintaining fiber 2310 (represented as having an elliptical core) is positioned between a first plate 2312 having a plurality of ridges 2314 formed thereon and a second generally flat plate 2316.

In a preferred embodiment, the (orthogonal) axes of the polarization-maintaining fiber 2310 are aligned with the direction of the pressure applied to the
30 fiber, for example, the slow axis of the fiber is parallel to the surface of the plate 2316, while the fast axis of the fiber is perpendicular to the surface of the plate 2316. In a polarization-maintaining fiber, at a given wavelength the two eigen-polarization

modes have very different mode effective indices n_{eff} . However, because the fiber
 cladding is circular, the cladding modes of the polarization-maintaining fiber have
 essentially the same effective indices n_{cl}^m for the two eigen-polarizations.
 Consequently, for a given cladding mode number m , the condition given by Equation
 1 is generally satisfied for different peak attenuation wavelength λ_m for the two
 5 polarizations. In other words, the attenuation peaks of the filter are widely separated,
 as illustrated in Figure 28A. In general, the bandwidth of each of these two
 attenuation notches should be smaller than the separation between notches $(\lambda_m^s - \lambda_m^f)$.
 How much smaller will depend on properties of the polarization-maintaining fiber, in
 particular on its birefringence. This filter acts as a polarizer that (1) rejects a first
 10 polarization but does not attenuate the second, orthogonal polarization at (and around)
 λ_m^f , and (2) rejects the second polarization but does not attenuate the first polarization
 at (and around) λ_m^s .

By increasing the separation of the peak attenuation wavelengths, the peak
 15 attenuation of light in one polarization is caused to occur at a wavelength for which
 the other polarization has less attenuation than its counterpart shown in Figure 13.
 Thus, the polarization-maintaining fiber in combination with the ridges of a long-
 period fiber grating can be used as an all-fiber polarizer.

A benefit of this embodiment is that the location of the peak wavelengths λ_m^s
 20 and λ_m^f can be tuned continuously over some finite range by rotating the fiber 2310
 about its axis prior to applying the pressure, so that the fast axis of the fiber 2310 lies
 at an angle θ with respect to the pressure plate 2316. The embodiment discussed in
 the previous paragraph corresponds to an axis angle $\theta=0^\circ$. By increasing this angle,
 the peak wavelengths λ_m^s and λ_m^f can be both varied continuously over some finite
 25 range, permitting adjustment of the polarizer so that it attenuates most strongly at the
 desired wavelength.

Figures 27A and 27B illustrate another embodiment of this invention utilizing
 an integrated optic waveguide 2500 to carry light and a plate 2510 having a plurality
 of ridges 2520 pressed against the surface of the waveguide. The waveguide 2500 is
 30 provided with a cladding region 2530 (2530') which can have one of several shapes,
 two of which are illustrated in Figure 27A and 27B. The plate 2510 acts to couple
 light from the fundamental (or a higher order) guided mode of the waveguide 2500 to

a guided mode of the cladding 2530 (2530'). This coupling is wavelength dependent, so that this device acts as a notch filter. The ridges 2520 on the pressure plate 2510 can be periodically spaced to produce the filter transmission function given by Equation 2. Alternatively, the ridges 2520 on the pressure plate 2510 can have an
5 arbitrary spatial distribution so as to produce a more complex filter transmission function. The cladding 2530 (2530') can be made of a composite and/or multilayer material, as discussed earlier, to minimize the temperature dependence of the filter transmission spectrum. The shape of the cladding 2530 (2530'), in particular its
10 diameter, controls the index of the cladding modes and can be tailored to produce the desired center wavelengths for the filter notches. In the configurations shown in Figures 27A and 27B, if the guide 2500 exhibits low birefringence, the filter transmission spectrum is slightly polarization dependent. On the other hand, if the guide 2500 exhibits high birefringence (comparable to what is readily achievable in integrated optic and fiber optics waveguides), the filter has a strongly polarization
15 dependent transmission spectrum and can be used as a polarizer. The ridges 2520 can then be chirped to widen the bandwidth of the polarizer, as described above in relation to fiber optic filters.

While preferred embodiments of this invention have been disclosed herein, those skilled in the art will appreciate that changes and modifications may be made therein
20 without departing from the spirit and scope of the invention as defined in the appended claims.

WHAT IS CLAIMED IS:

1. A method of forming an optical filter, comprising:
 applying pressure at various points along a segment of an optical waveguide to induce perturbations in the refractive index and create a grating within the waveguide, the segment being less than approximately 5 cm in length;
 5 and
 selecting the pressure and relative spacings between the pressure points such that optical radiation passing through the waveguide is more strongly attenuated at some wavelengths than at other wavelengths.
- 10 2. The method of Claim 1, wherein the waveguide includes a single mode fiber.
3. An optical filter, comprising:
 an optical waveguide; and
 a device for maintaining pressure along less than about 5 cm of said
 15 waveguide to induce local changes in the index of refraction, the induced changes in the index of refraction creating an optical grating within said waveguide that attenuates optical radiation passing through said waveguide more strongly at some wavelengths than at other wavelengths.
4. The optical filter of Claim 3, wherein said optical waveguide includes
 20 a single mode fiber.
5. The optical filter of Claim 3, in which said waveguide is polarization maintaining to vary the polarization dependence of the attenuated optical radiation.
6. The optical filter of Claim 3, said device comprising two plates, one of said plates having ridges for applying pressure to said waveguide.
- 25 7. The optical filter of Claim 6, said ridged plate having a plurality of periodically spaced ridges for applying pressure to said waveguide.
8. A method of forming an optical filter, comprising:
 applying pressure at various points along a segment of an optical waveguide having a cladding, to induce perturbations in the refractive index and
 30 create a grating within the optical waveguide, the segment being less than approximately 5 cm in length; and

selecting the pressure and the relative spacings between the pressure points such that optical radiation passing through the optical waveguide is more strongly coupled into the cladding at some wavelengths than at other wavelengths, so that the waveguide acts as an optical filter.

5 9. The method of Claim 8, wherein the optical waveguide includes a single mode fiber.

10 10. A method of forming an optical filter having reduced polarization dependence, comprising:

 applying pressure to an optical waveguide by pressing the waveguide
10 into a plurality of periodically spaced grooves that are generally V-shaped, said applied pressure inducing perturbations in the refractive index of the waveguide to create a grating within the waveguide, the pressure being applied in substantially equal measure between orthogonal axes; and

 selecting the relative spacings between the pressure points such that
15 optical radiation passing through the waveguide is more strongly attenuated at some wavelengths than at other wavelengths, so that the waveguide acts as an optical filter.

 11. The method of Claim 10, wherein the optical waveguide includes a single-mode optical fiber.

20 12. An optical filter, comprising:
 an optical waveguide; and

 a device for maintaining pressure along said waveguide to induce local
 changes in the index of refraction, the induced changes in the index of refraction
 creating an optical grating within said waveguide that attenuates optical radiation
25 passing through said waveguide more strongly at some wavelengths than at other wavelengths, said device having periodically spaced, generally V-shaped grooves for receiving said waveguide, said V-shaped grooves causing the pressure to be applied substantially equally between orthogonal axes of said filter to reduce the polarization dependence of said filter.

30 13. The optical filter of Claim 12, wherein said waveguide includes a single-mode optical filter.

14. A method of forming an optical filter, comprising:

applying pressure to an optical waveguide by pressing the waveguide into a groove that passes through a plurality of periodically spaced ridges, said groove being generally V-shaped within said ridges, said applying pressure inducing perturbations in the refractive index of the waveguide to create a grating within the waveguide, the pressure being applied substantially equally between orthogonal axes of the waveguide;

selecting the relative spacings between the ridges such that optical radiation passing through the waveguide is more strongly attenuated at some wavelengths than at other wavelengths, so that the waveguide acts as an optical filter.

15. The method of Claim 14, wherein the optical waveguide includes a single mode optical fiber.

16. The method of Claim 14, further comprising simultaneously applying pressure to the waveguide by pressing the waveguide into a second groove, the second groove being generally V-shaped.

17. An optical filter, comprising:

an optical waveguide; and

a device for maintaining pressure along said waveguide to induce local changes in the index of refraction, the induced changes in the index of refraction creating an optical grating within said waveguide that attenuates optical radiation passing through said waveguide more strongly at some wavelengths than at other wavelengths, said device having at least one groove for receiving said waveguide, said groove passing through a plurality of periodically spaced ridges where said groove is generally V-shaped, said groove causing the pressure to be applied substantially equally between orthogonal axes of said waveguide.

18. The optical filter of Claim 17, wherein said optical waveguide includes a single-mode optical fiber.

19. The optical filter of Claim 17, further comprising a second groove for receiving said waveguide, said second groove passing through said plurality of periodically spaced ridges, said second groove being non-parallel with respect to said first groove, the period of said ridges of said second groove causing said filter to

attenuate light more strongly at different wavelengths than when said waveguide is in said first groove.

20. A method of forming an optical chirped grating, comprising:

5 applying pressure at various points along an optical waveguide by urging the waveguide into a V-shaped groove to induce perturbations in the refractive index and create a grating within the waveguide; and

10 selecting the relative spacings between the pressure points such that optical radiation passing through the waveguide is more strongly attenuated at some wavelengths than at other wavelengths, so that the waveguide acts as an optical filter, wherein the relative spacings are aperiodic to broaden the linewidth of the attenuation of the filter.

21. The method of Claim 20, wherein the optical waveguide includes a single-mode optical fiber.

22. An optical chirped grating, comprising:

15 an optical waveguide; and

20 a device for maintaining pressure along said waveguide to induce local changes in the index of refraction by urging said waveguide into a V-shaped groove, the induced changes in the index of refraction creating an optical grating within said waveguide that attenuates optical radiation passing through said waveguide more strongly at some wavelengths than at other wavelengths, said device comprising ridges for applying pressure to said waveguide, wherein pressure is applied to said waveguide aperiodically.

23. The grating of Claim 22, wherein said optical waveguide includes a single-mode optical fiber.

25 24. The chirped grating of Claim 22, wherein said ridges are spaced aperiodically from each other.

25. The chirped grating of Claim 22, wherein said ridges are spaced periodically from each other, but said waveguide is bent with respect to said rows such that said ridges make aperiodic contact with said waveguide.

30 26. An optical filter, comprising:

an optical waveguide, said waveguide including a core for propagating a fundamental mode and a cladding surrounding said single mode waveguide;

a first device for maintaining pressure at a first plurality of periodically spaced pressure points along said waveguide so that the index of said waveguide is perturbed periodically, the period between said first pressure points and the pressure applied to said first pressure points selected to couple the fundamental mode to a cladding mode of said cladding;

a second device for maintaining pressure at a second plurality of periodically spaced pressure points along said waveguide so that the index of said waveguide is perturbed periodically, the period between said second pressure points and the pressure applied to said second pressure points selected to couple the fundamental mode to a cladding mode of said cladding, wherein the pressure applied by said first device and the pressure applied by said second device are applied in different directions to reduce the polarization dependence of light transmitted through said filter.

27. The filter of Claim 26, wherein said optical waveguide includes a single-mode optical fiber.

28. The filter of Claim 26, wherein said first device and said second device include devices which apply pressure to said waveguide with azimuthal symmetry to further reduce the polarization dependence of said filter.

29. The filter of Claim 26, wherein the pressure applied by said first device and the pressure applied by said second device are applied in substantially orthogonal directions, so that said filter is substantially polarization independent.

30. An optical filter, comprising:

an optical waveguide, said waveguide including a core and a cladding;
and

a device for maintaining pressure at a plurality of points periodically spaced along said waveguide, the pressure inducing perturbations in the refractive index of said waveguide and creating an optical grating within said waveguide, so that a fundamental core mode of said waveguide is coupled to a cladding mode of said waveguide more strongly at some wavelengths than at other wavelengths to produce an optical filter, said device applying pressure to said waveguide with azimuthal symmetry that is at least 3-fold, so that light

incident on said waveguide passes through said waveguide substantially independently of the polarization of the incident light.

31. The filter of Claim 30, wherein said optical waveguide includes a single-mode optical fiber.

5 32. The filter of Claim 30, wherein said device comprises a cylinder having an inner surface, said cylinder including ridges that adjoin the inner surface and apply pressure to said waveguide.

33. The filter of Claim 30, wherein said cylinder is divided into more than one piece, wherein said pieces are clamped together to form said cylinder.

10 34. The filter of Claim 30, wherein said device comprises two plates that compress said waveguide, one of said plates having a series of ridges through which a first groove is cut, said first groove receiving said waveguide.

35. The filter of Claim 34, including a second groove for receiving said waveguide, wherein said second groove is cut through said ridges at an angle different from said first groove, such that said filter has transmission properties that depend upon
15 which of said grooves receives said waveguide.

36. The filter of Claim 34, wherein said groove intersects with said ridges to form a V-shape.

37. The filter of Claim 34, wherein both of said plates have grooves therein, such that said waveguide can be simultaneously received by both a groove in said first
20 plate and a groove in said second plate.

38. An optical filter, comprising:

an optical waveguide, said waveguide including a core and a cladding;
and

25 a device for maintaining pressure at a plurality of points aperiodically spaced along said waveguide, the pressure inducing perturbations in the refractive index of said waveguide and creating a chirped optical grating within said waveguide, so that a fundamental core mode of said waveguide is coupled to a cladding mode of said waveguide more strongly at some wavelengths than at
30 other wavelengths to produce an optical filter.

39. The filter of Claim 38, wherein said optical waveguide includes a single-mode optical fiber.

40. The filter of Claim 38, said device applying pressure to said waveguide with azimuthal symmetry that is at least 3-fold, so that light incident on said waveguide passes through said waveguide substantially independently of the polarization of the incident light.

5 41. The filter of Claim 38, said device applying pressure to said waveguide asymmetrically so that said filter is polarization dependent.

42. An optical polarizer, comprising:
a high-birefringence optical waveguide having birefringent axes; and
a device for applying pressure at various points along said waveguide to
10 induce local changes in the index of refraction, the induced changes in the index of refraction creating an optical grating within said waveguide that attenuates optical radiation passing through said waveguide more strongly at some wavelengths than at other wavelengths, one of the birefringent axes being aligned with the direction of the pressure applied by said device.

15 43. The polarizer of Claim 42, wherein said optical waveguide includes a single-mode optical fiber.

44. The polarizer of Claim 42, said waveguide being rotatable within said device about a longitudinal axis of said waveguide to vary how optical radiation passing through said waveguide is attenuated as a function of wavelength.

20 45. The polarizer of Claim 42, wherein the pressure points are aperiodically spaced along said waveguide to increase the spectral range over which said filter acts as a polarizer.

46. The polarizer of Claim 45, wherein pressure is applied to said waveguide with a ridged plate.

25 47. The filter of Claim 46, wherein said ridges are aperiodically spaced on said plate.

48. The filter of Claim 46, wherein said ridges are periodically spaced on said plate, said waveguide being bent along an arcuate curve with respect to said ridges.

30 49. An optical polarizer, comprising:
an integrated optic waveguide for propagating a fundamental mode and a substrate mode; and

5 a plate having ridges pressed against said waveguide, said ridges applying pressure at points along said waveguide so that, for light coupled into said waveguide, a first polarization of the light is coupled more strongly from the fundamental mode to the substrate mode than is the polarization of light orthogonal to the first polarization, leading to preferential attenuation of the first polarization of the light.

50. The polarizer of Claim 49, wherein the orthogonal polarization is substantially uncoupled to the substrate mode.

10 51. The polarizer of Claim 49, wherein said ridges are spaced aperiodically from each other to increase the spectral range over which said polarizer operates.

52. An optical filter, comprising:
 an optical waveguide; and
 a device for maintaining pressure along at least a portion of said waveguide, said device including rows of ridges, said ridges contacting said waveguide at various points along said waveguide to induce local changes in the index of refraction, the induced changes in the index of refraction creating an optical grating within said waveguide that attenuates optical radiation passing through said waveguide more strongly at some wavelengths than at other wavelengths, said rows periodically spaced from each other such that said points are periodically spaced from each other, said rows having different lengths such that the length of said portion over which pressure is maintained can be varied by positioning said waveguide at different locations on said device without changing the periodicity between said points.

25 53. The optical filter of Claim 52, wherein said optical waveguide includes a single-mode fiber.

30 54. A method of forming an optical filter, comprising:
 keeping an optical waveguide under tension to avoid microbending;
 applying pressure at various points along a segment of the waveguide to induce perturbations in the refractive index and create a grating within the waveguide; and

selecting the pressure and relative spacings between the pressure points such that optical radiation passing through the waveguide is more strongly attenuated at some wavelengths than at other wavelengths.

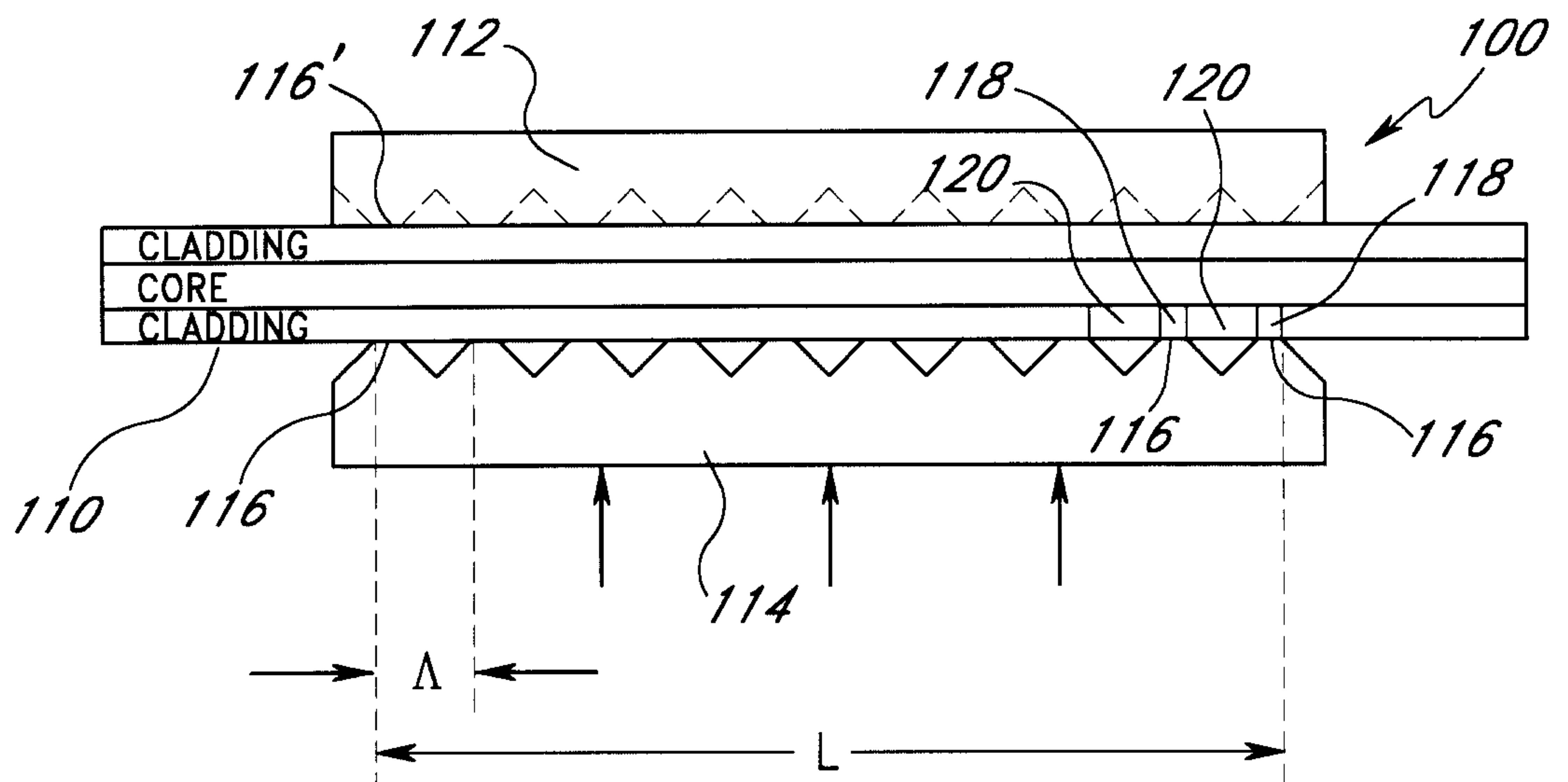


FIG. 1

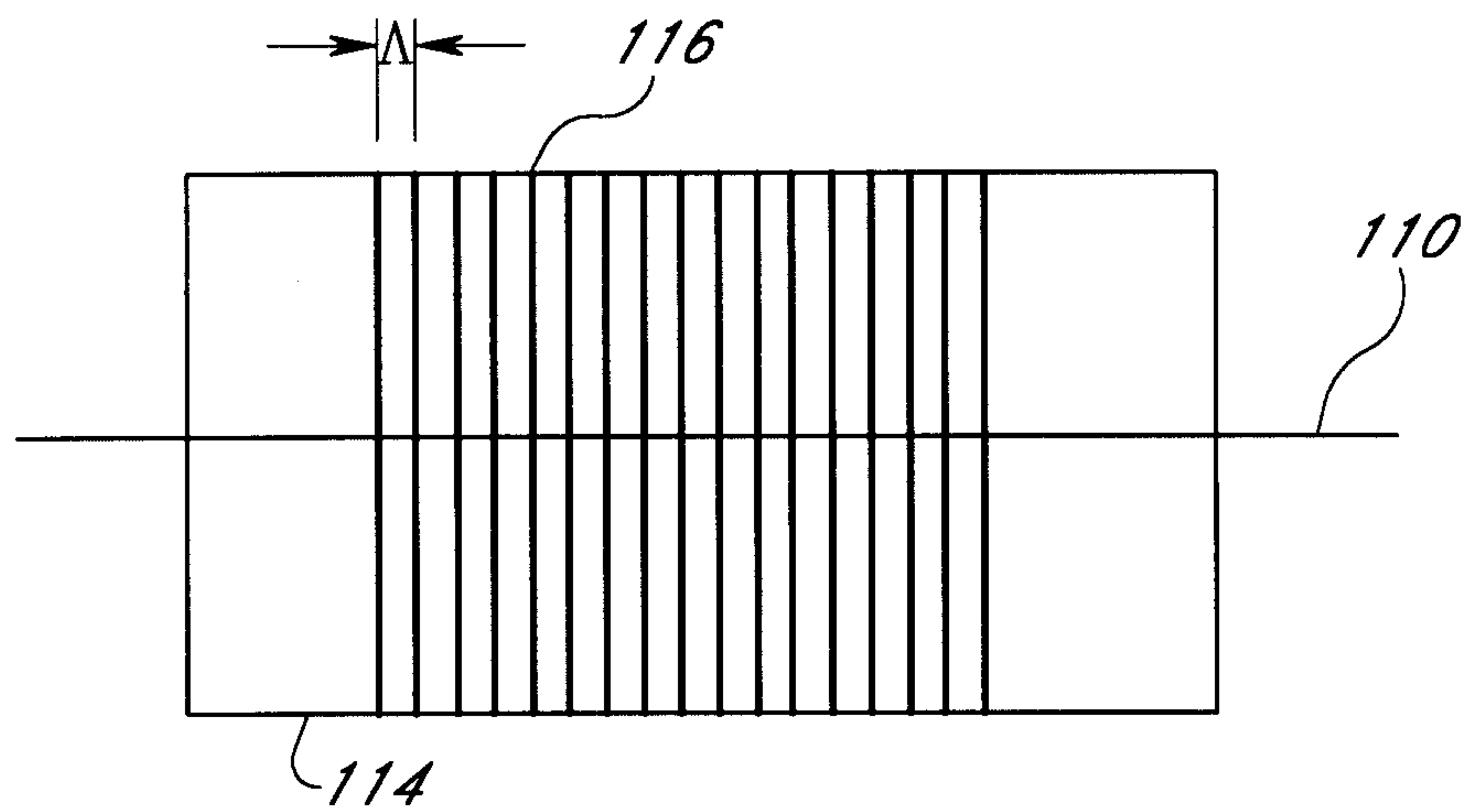


FIG. 2A

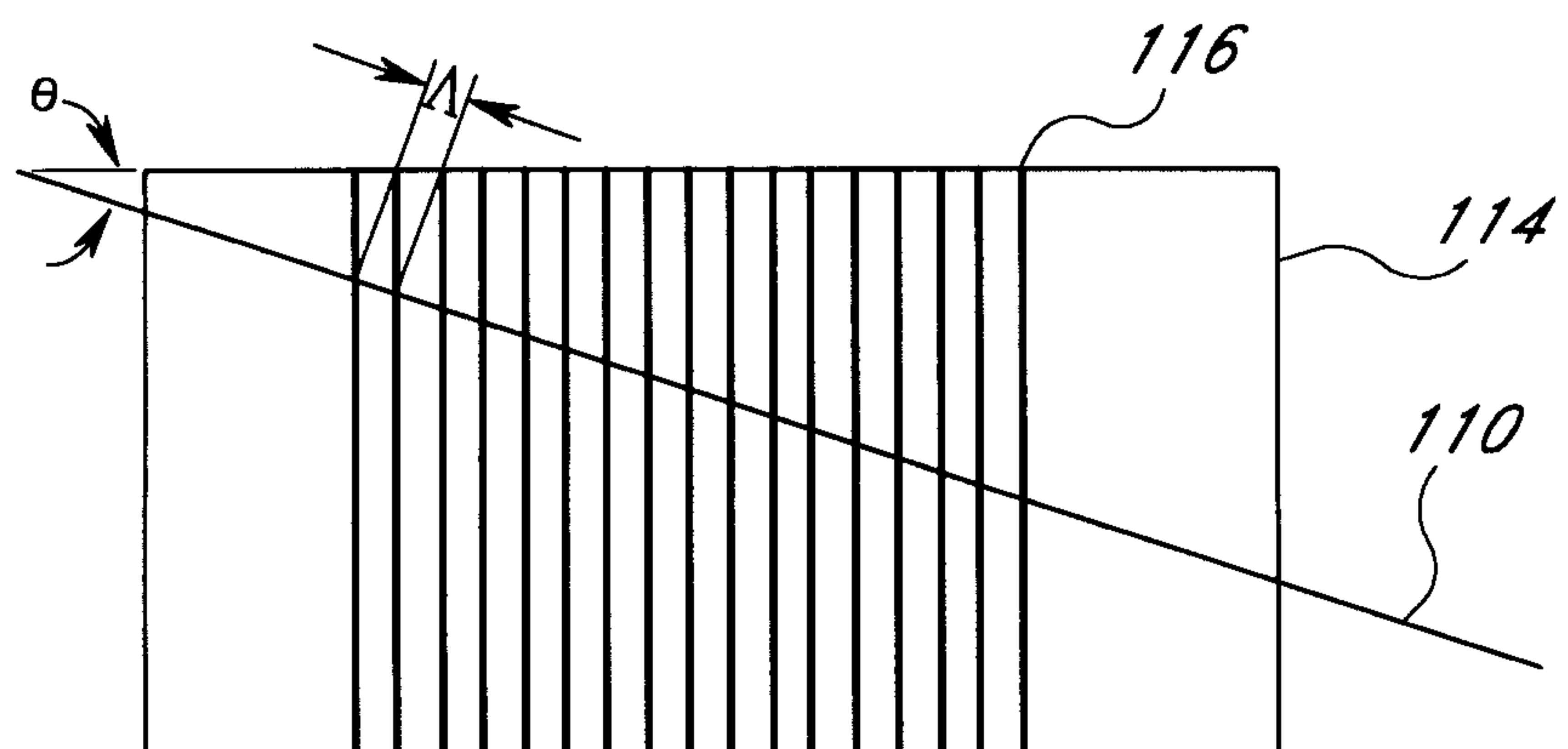


FIG. 2B

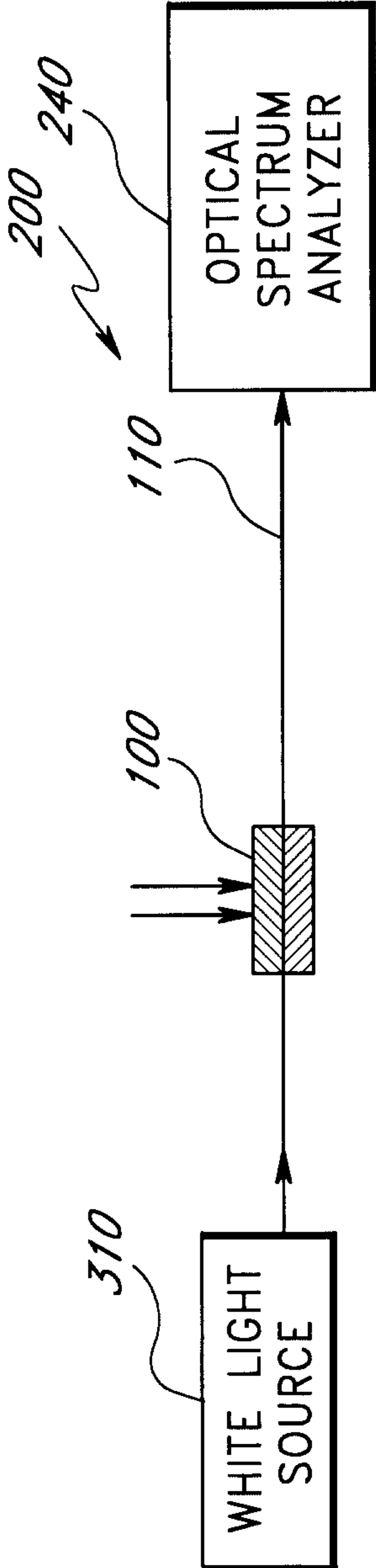


FIG. 3A

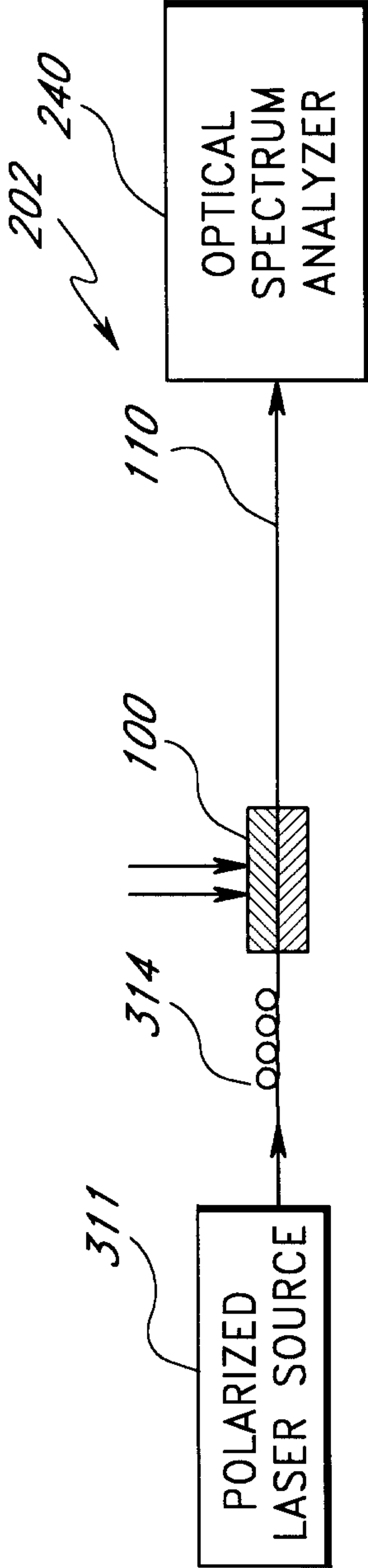
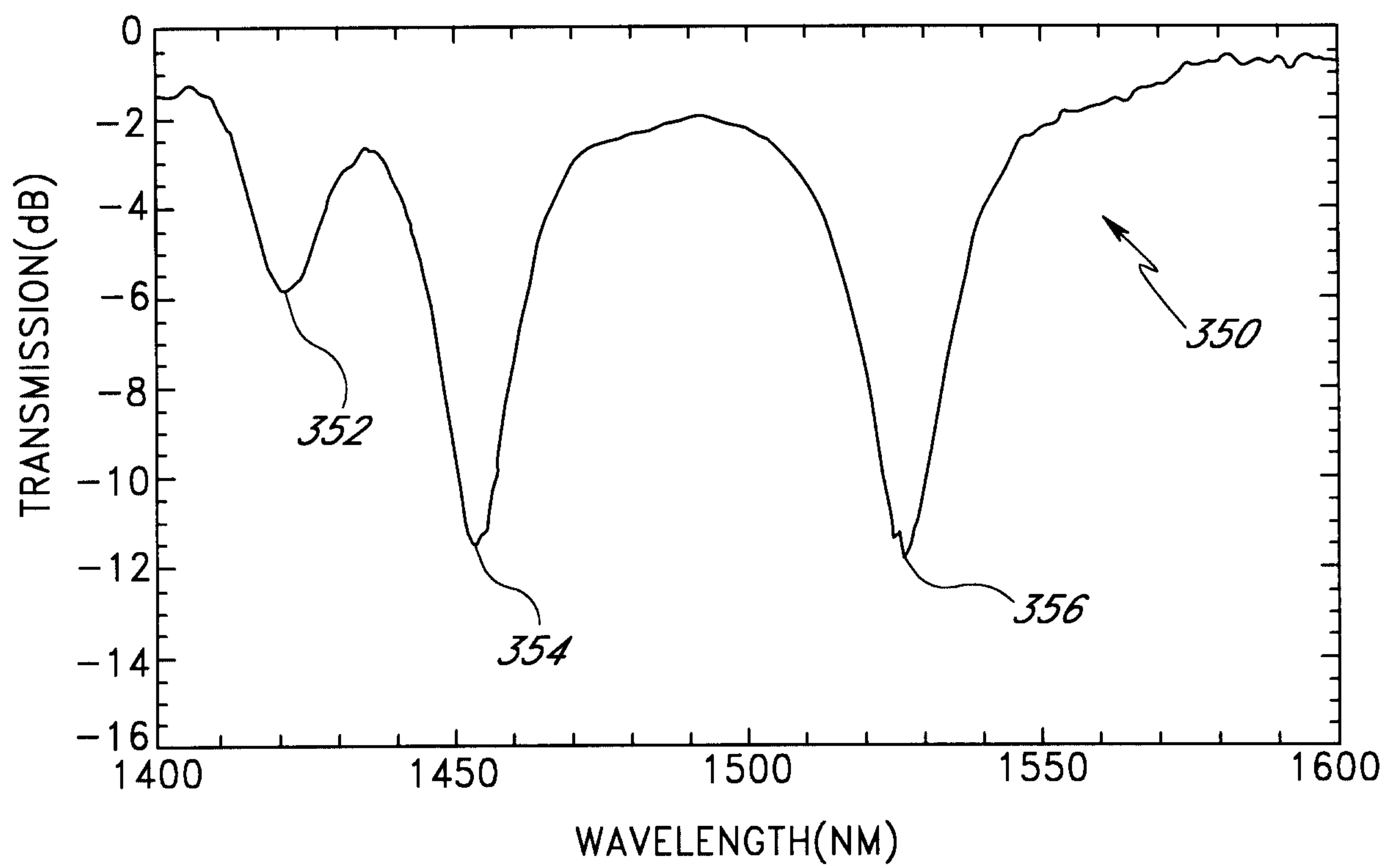
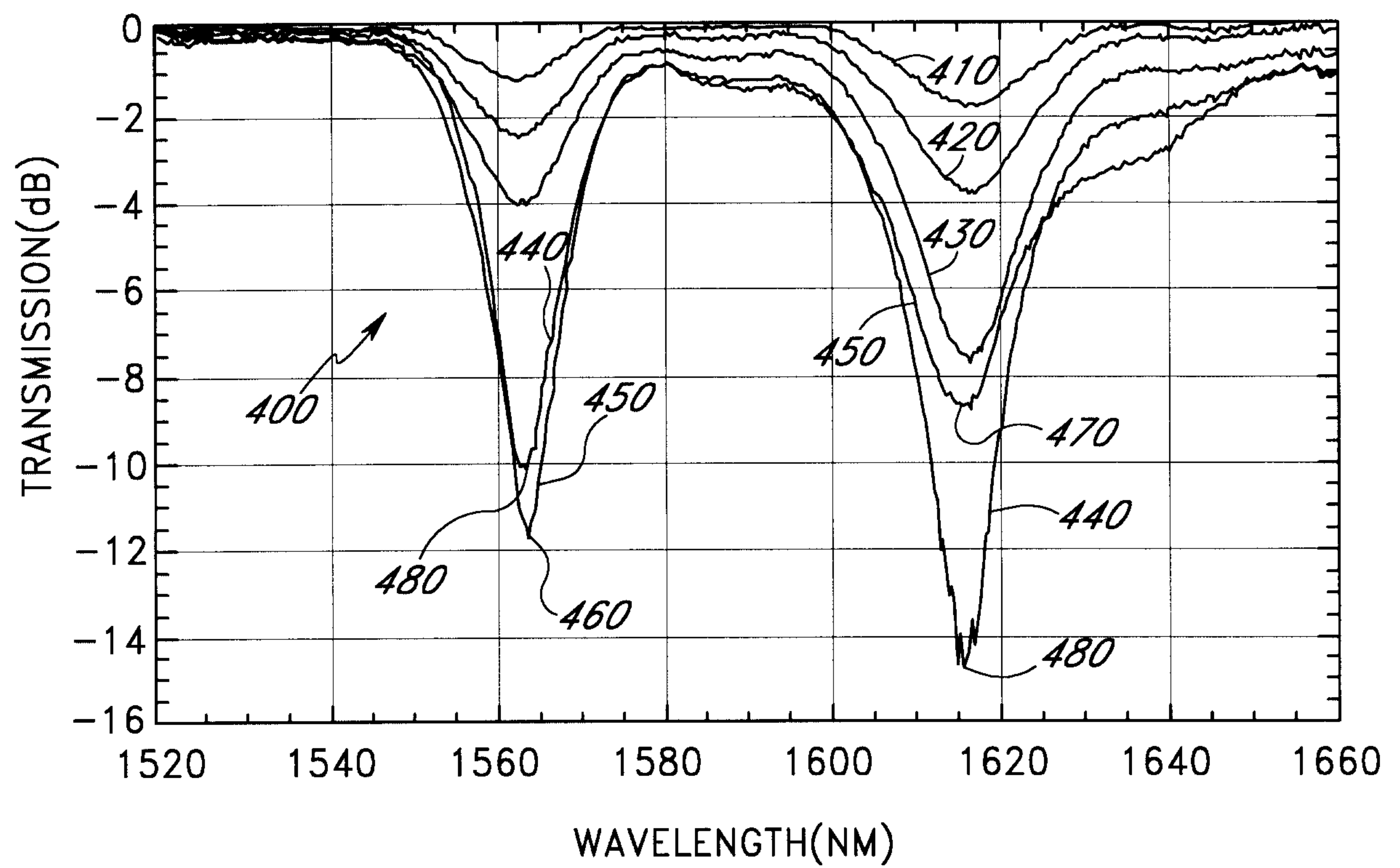
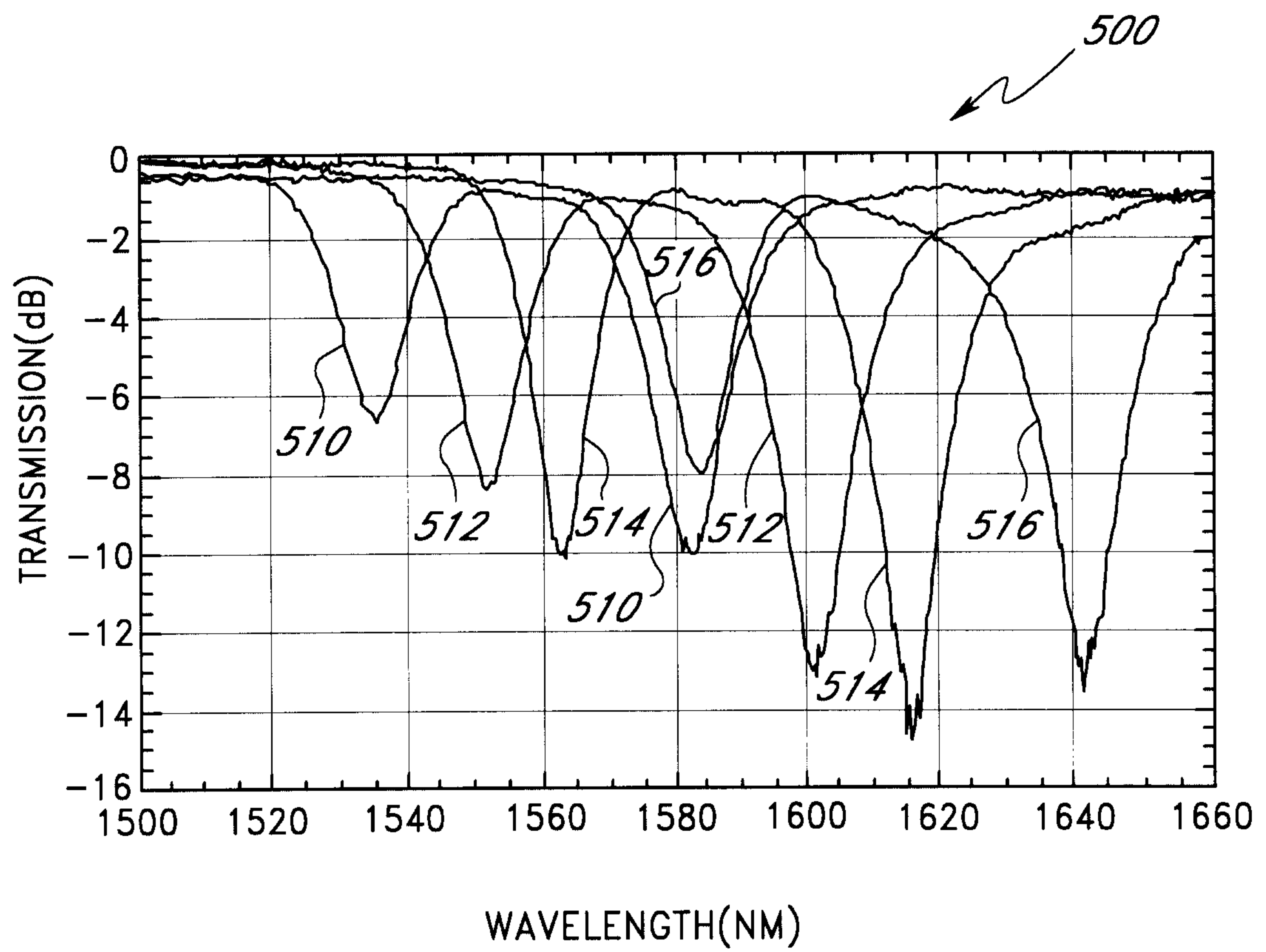
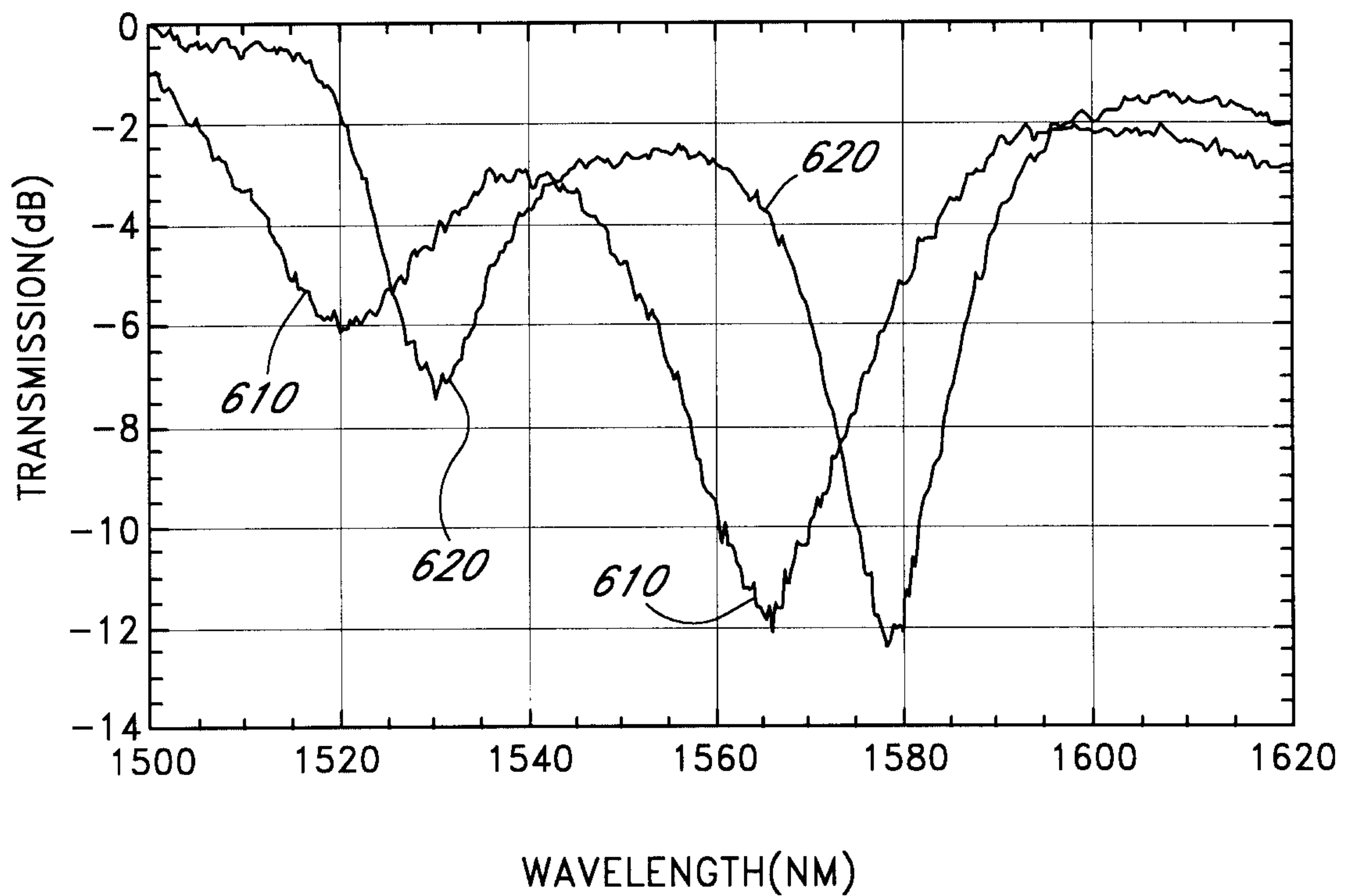


FIG. 3B

**FIG. 4****FIG. 5**

**FIG. 6****FIG. 7**

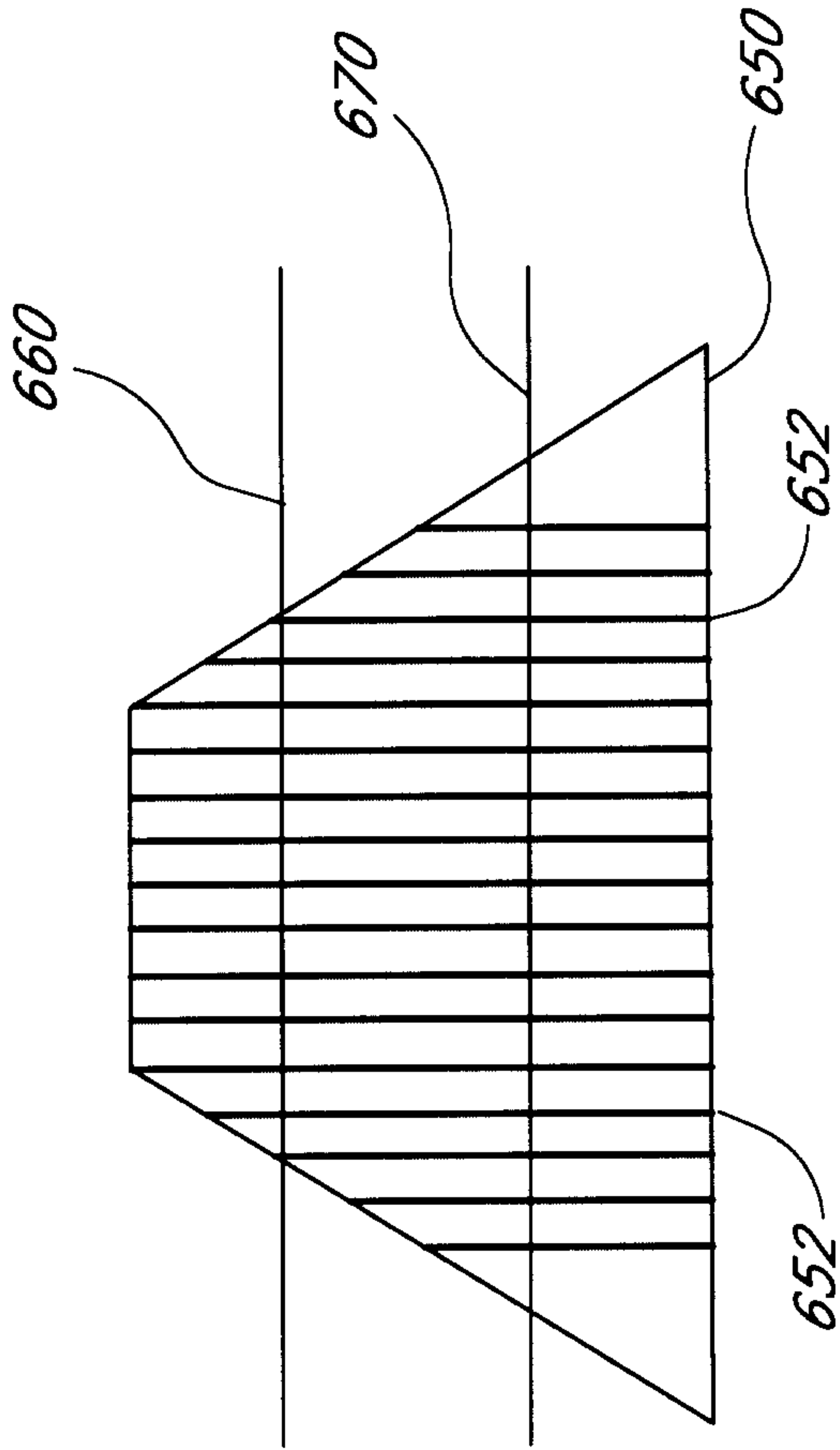


FIG. 8

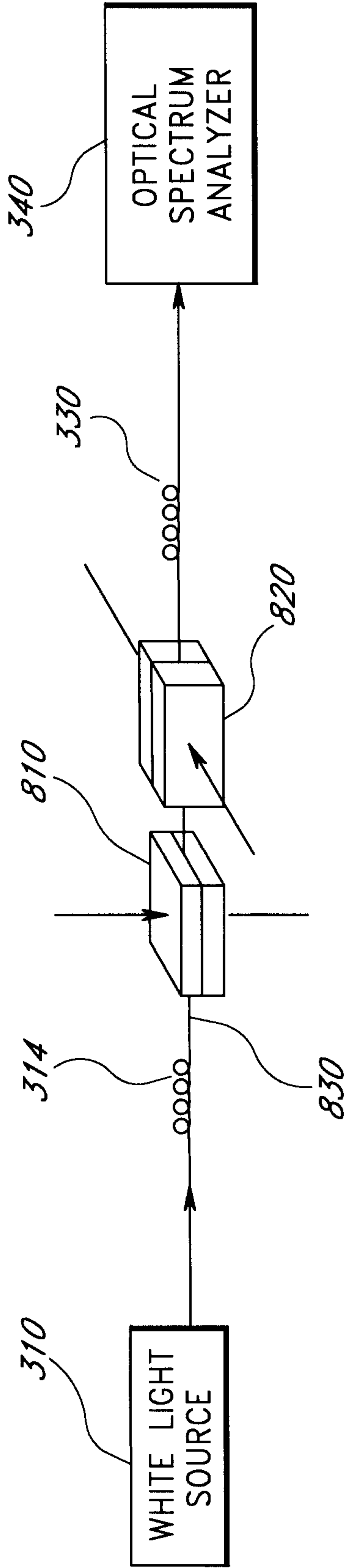


FIG. 9

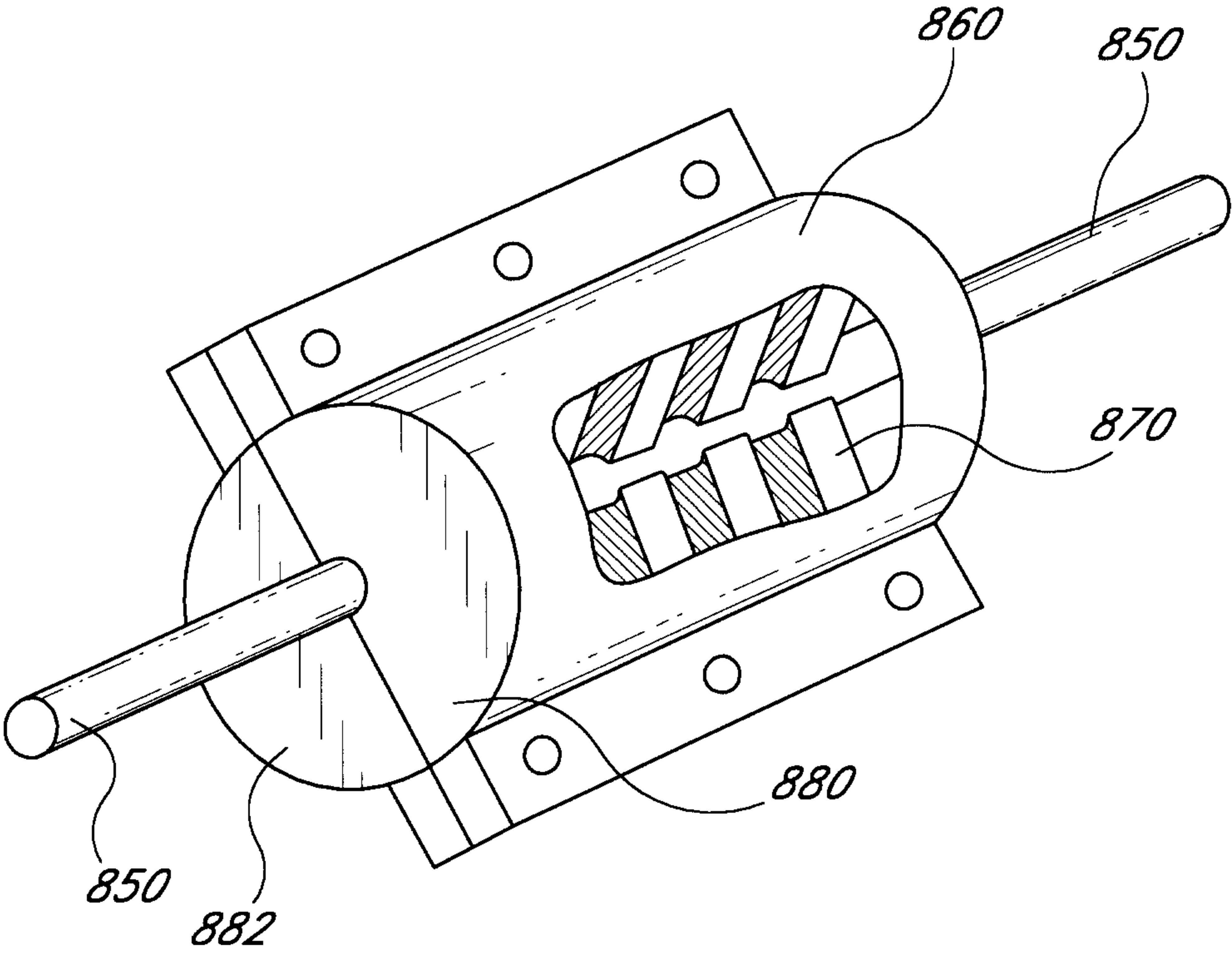


FIG. 10

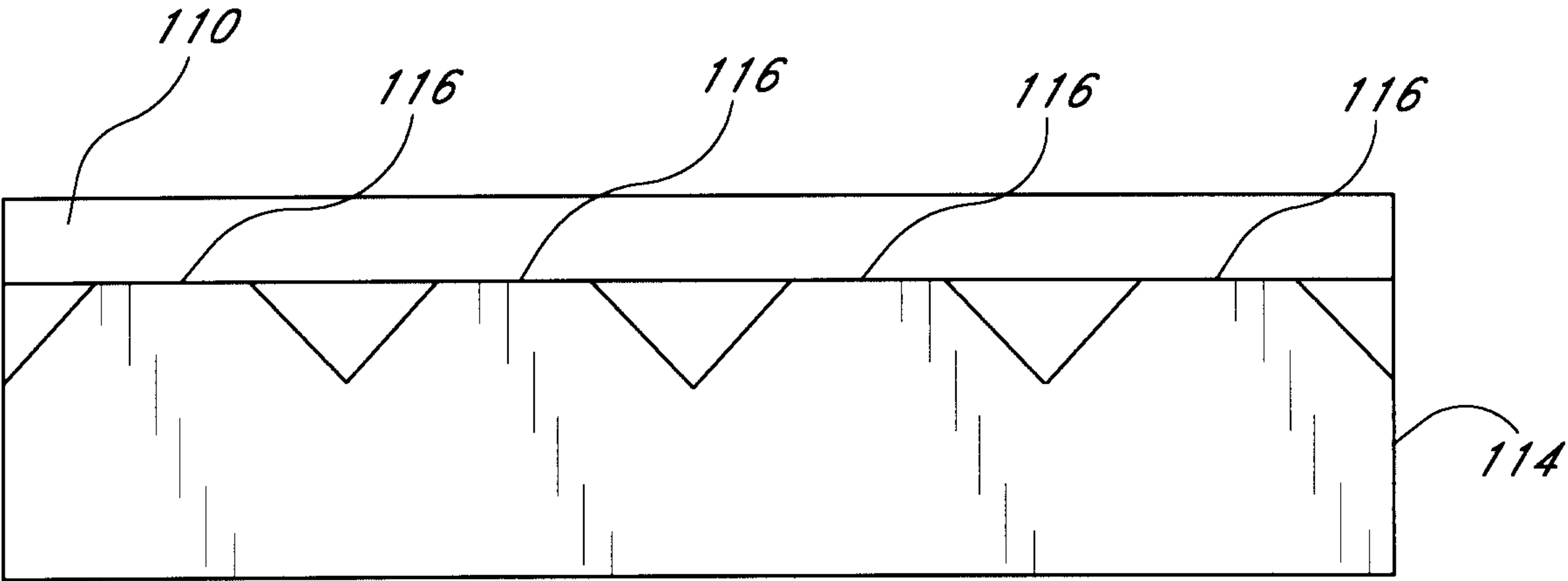


FIG. 11

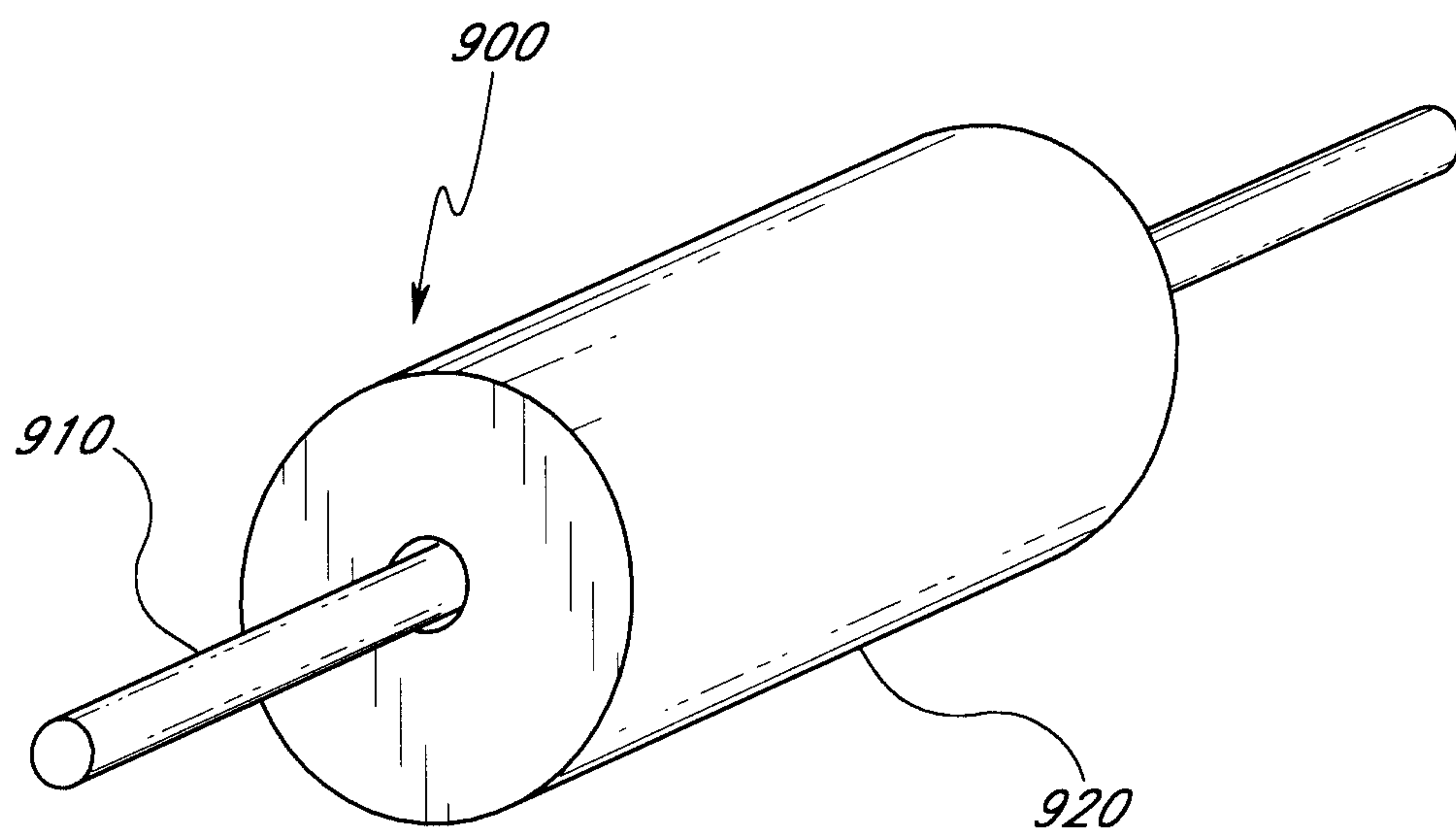


FIG. 12A

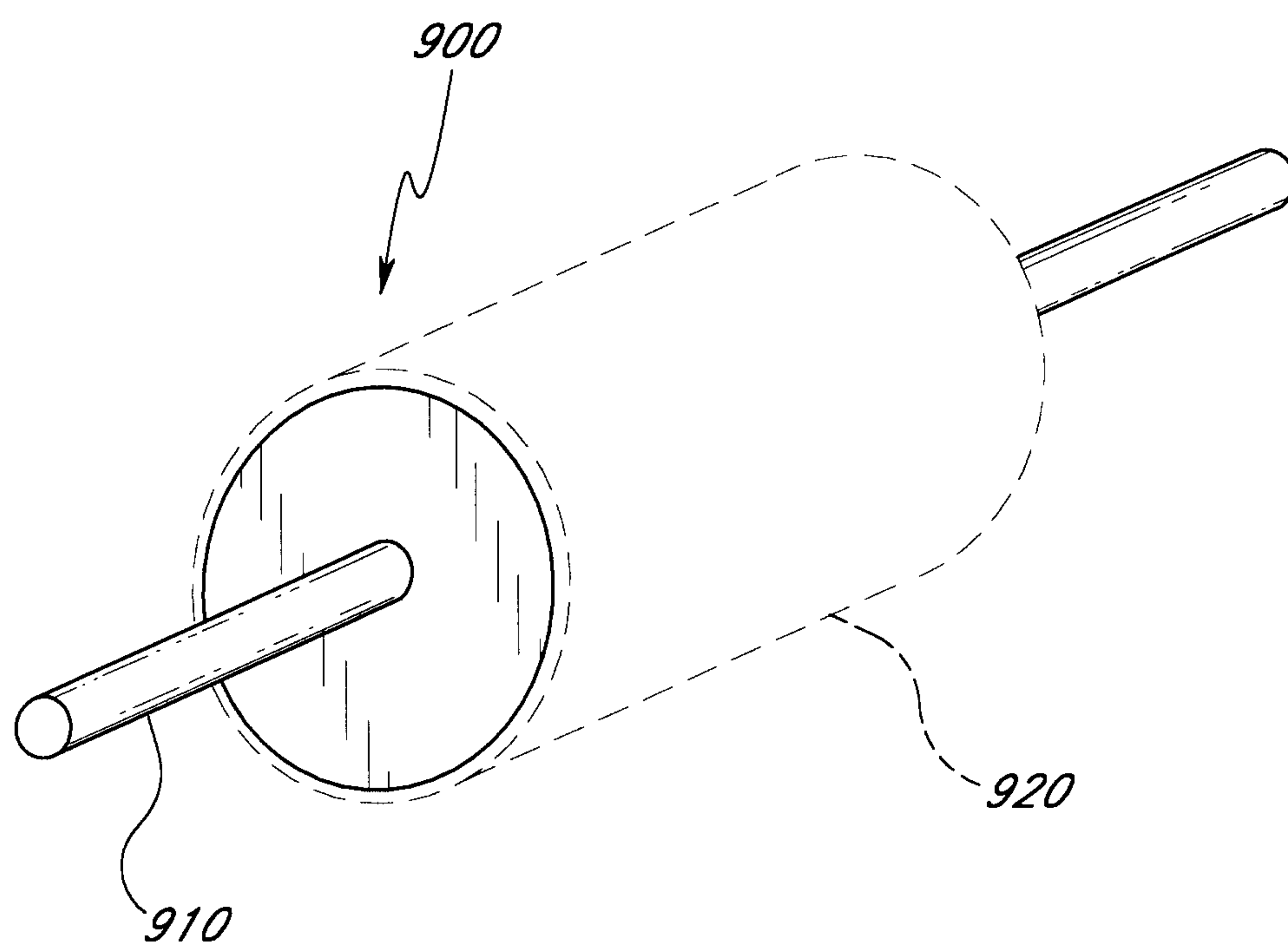
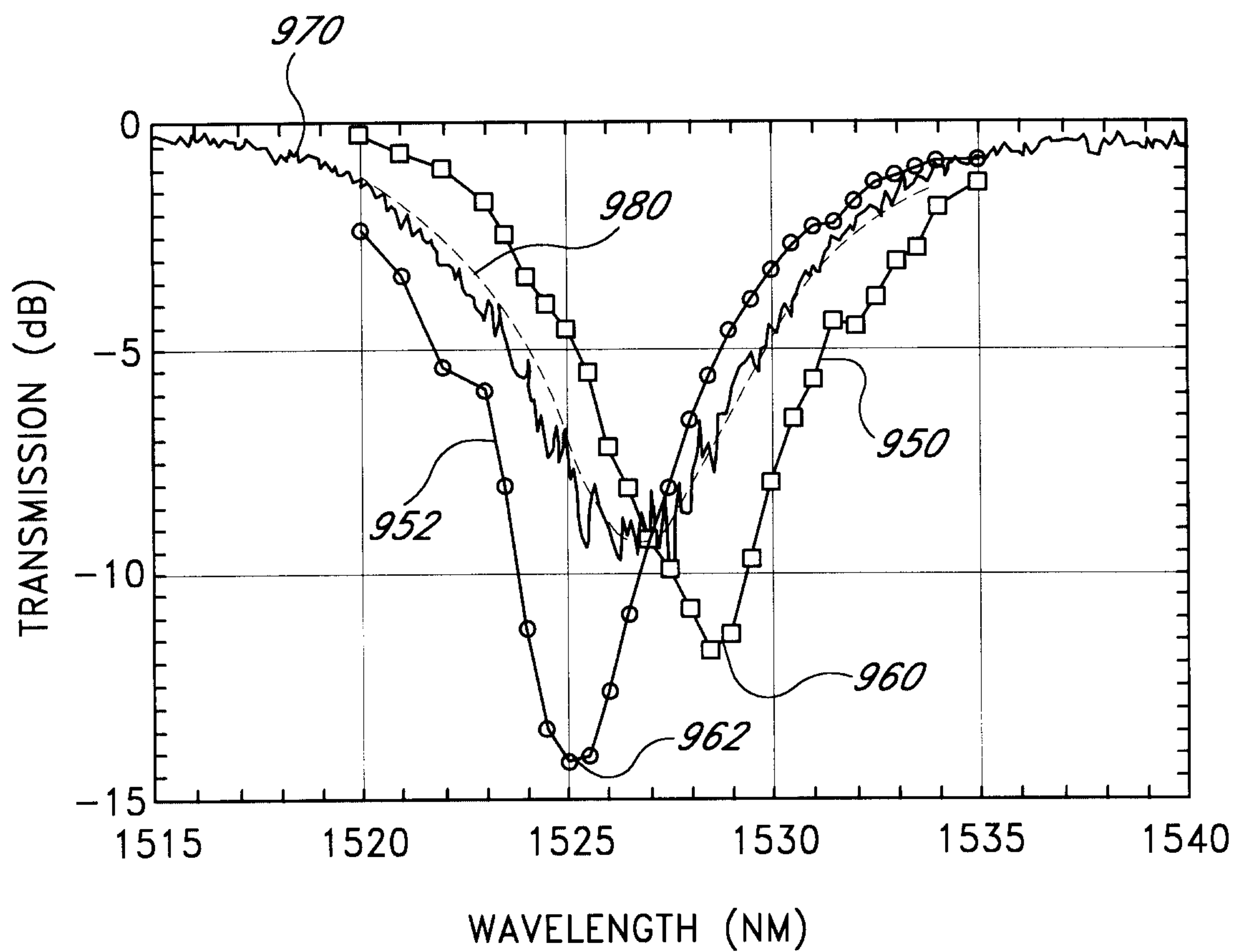
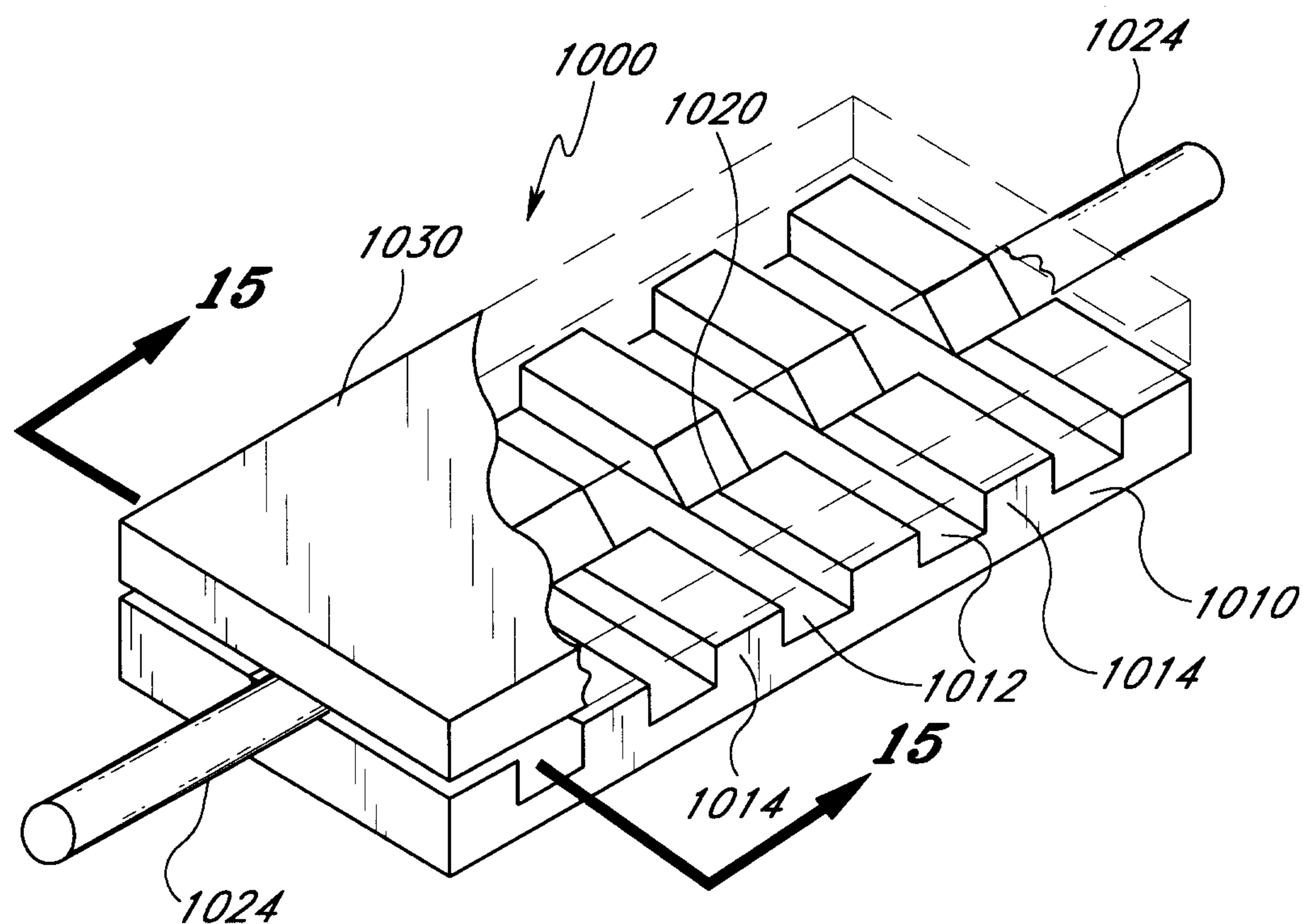


FIG. 12B

**FIG. 13****FIG. 14**

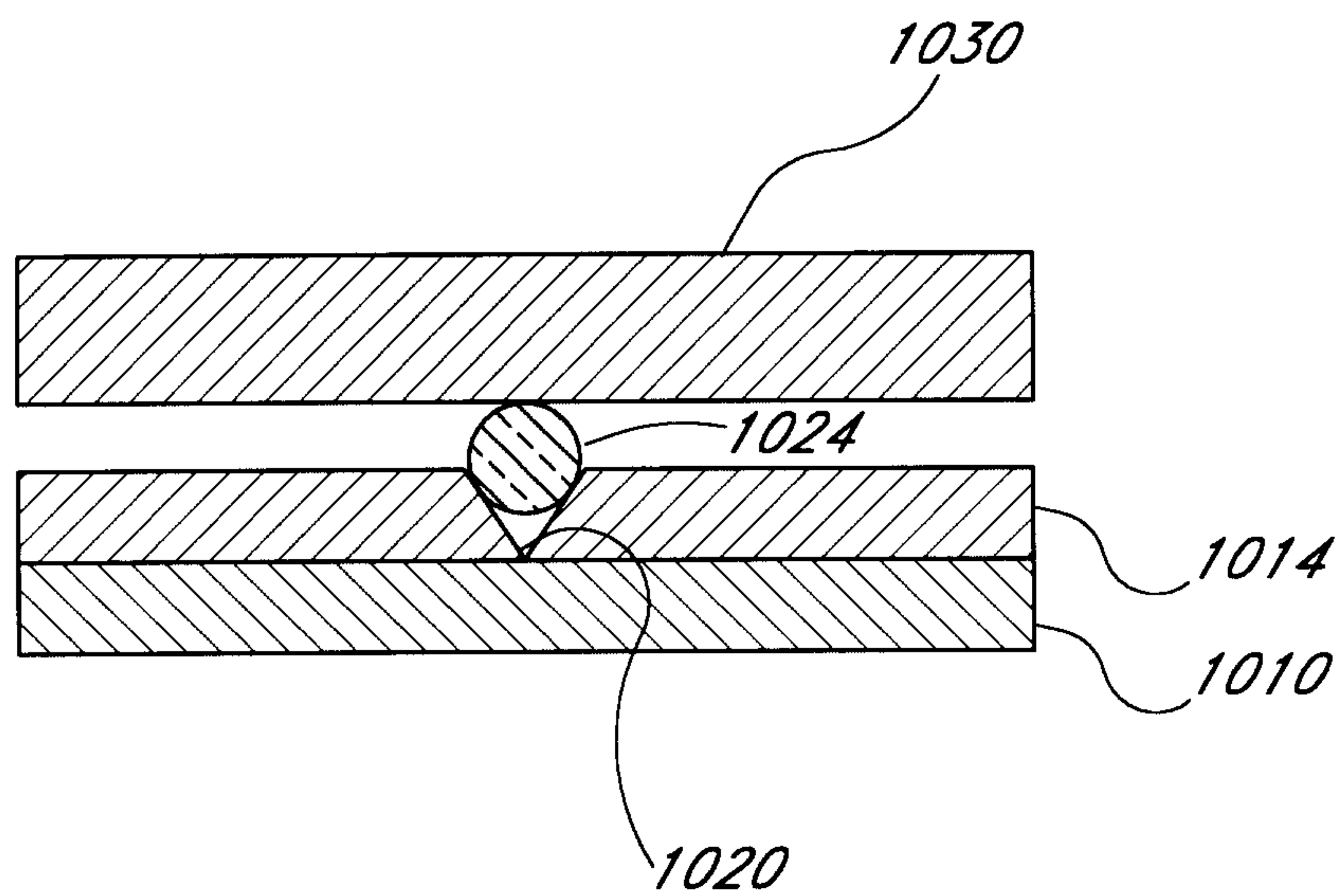


FIG. 15

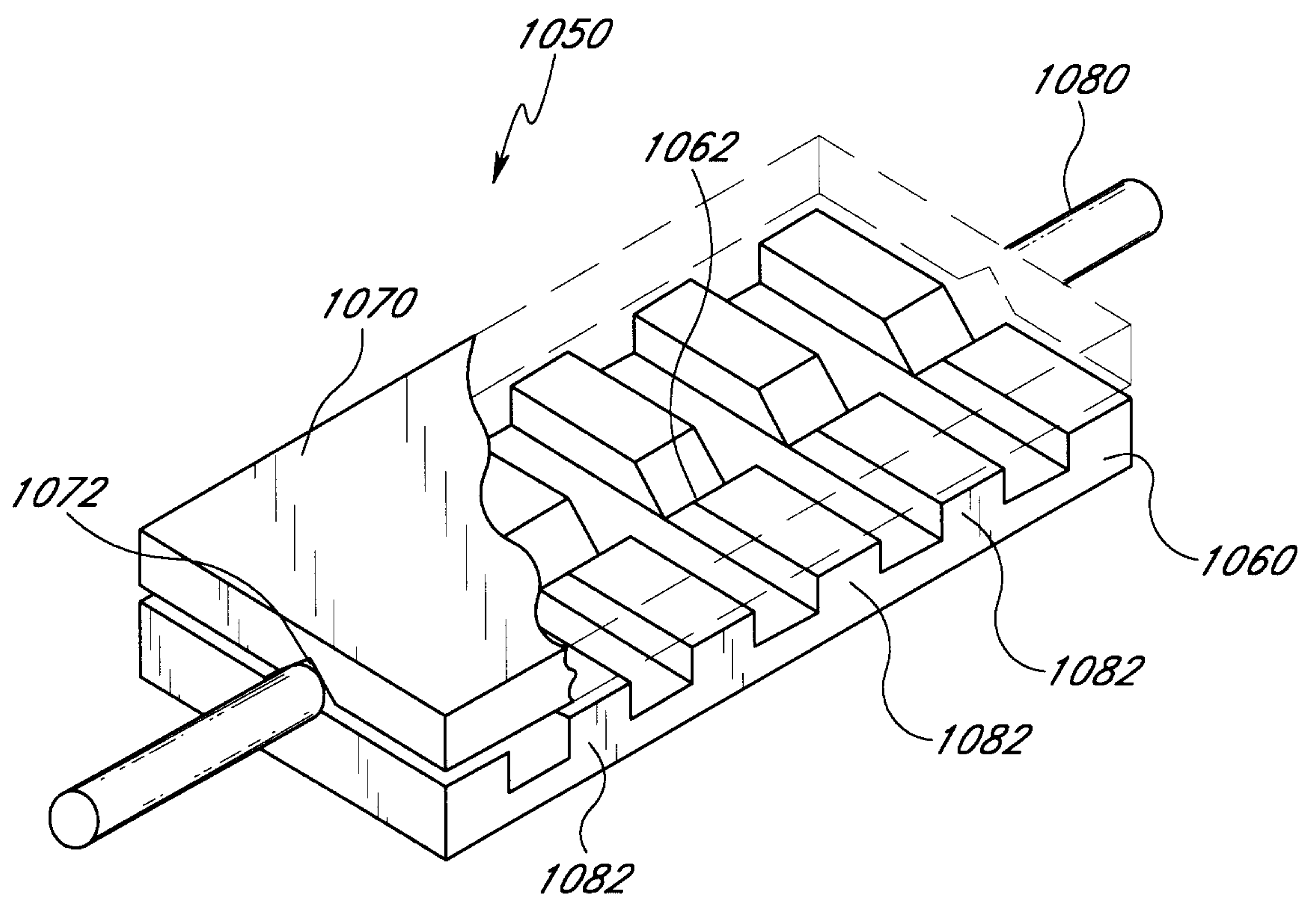


FIG. 16

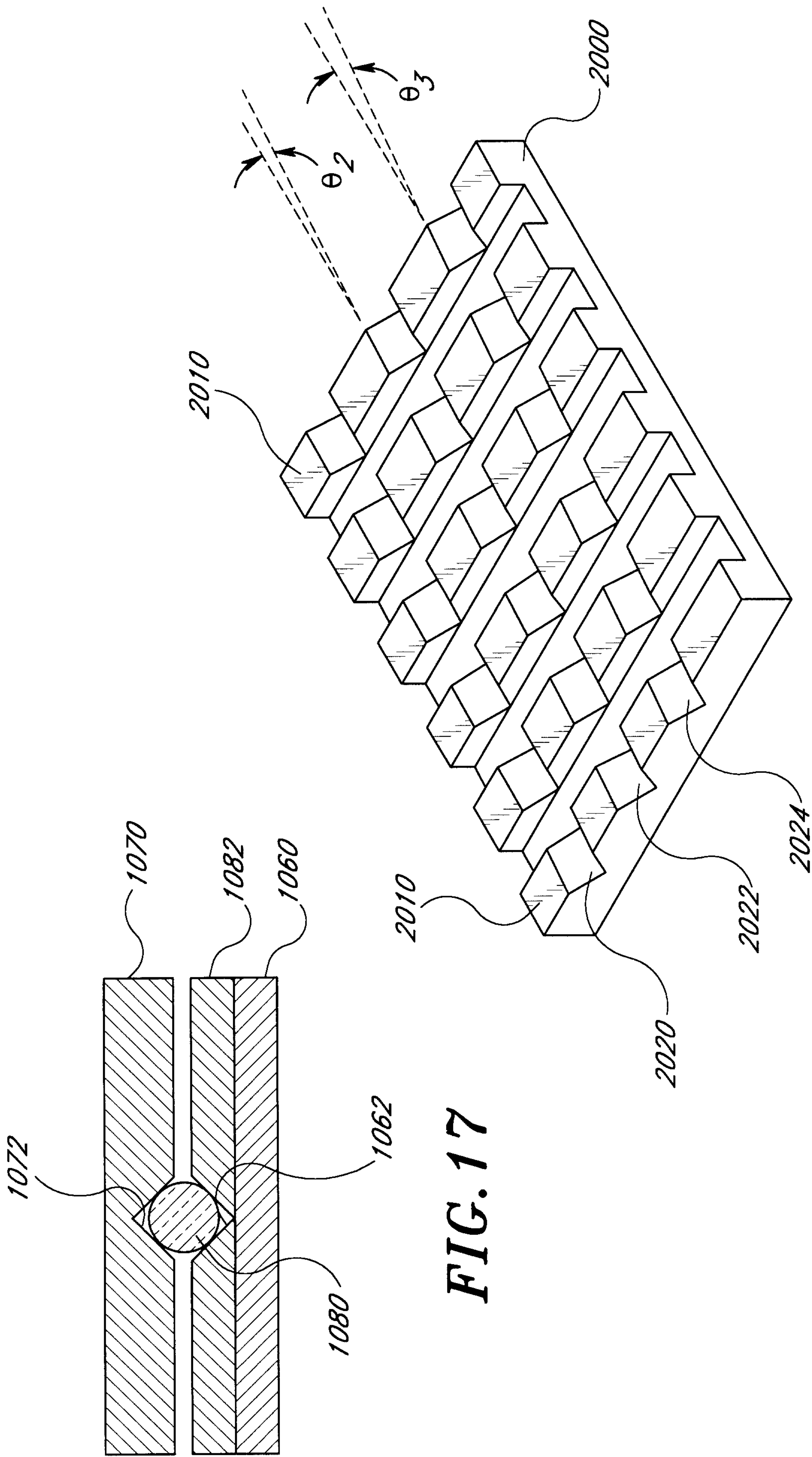
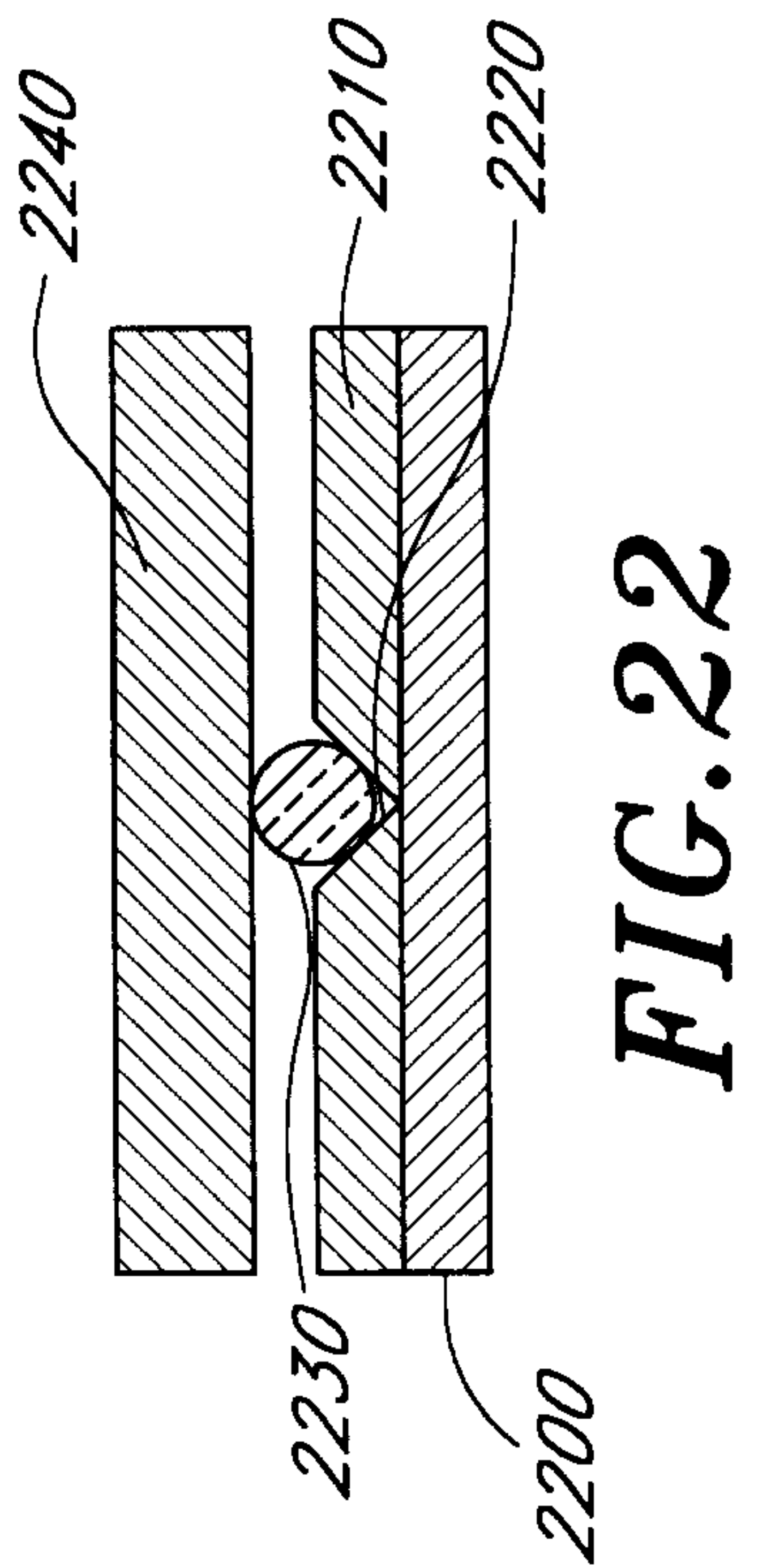
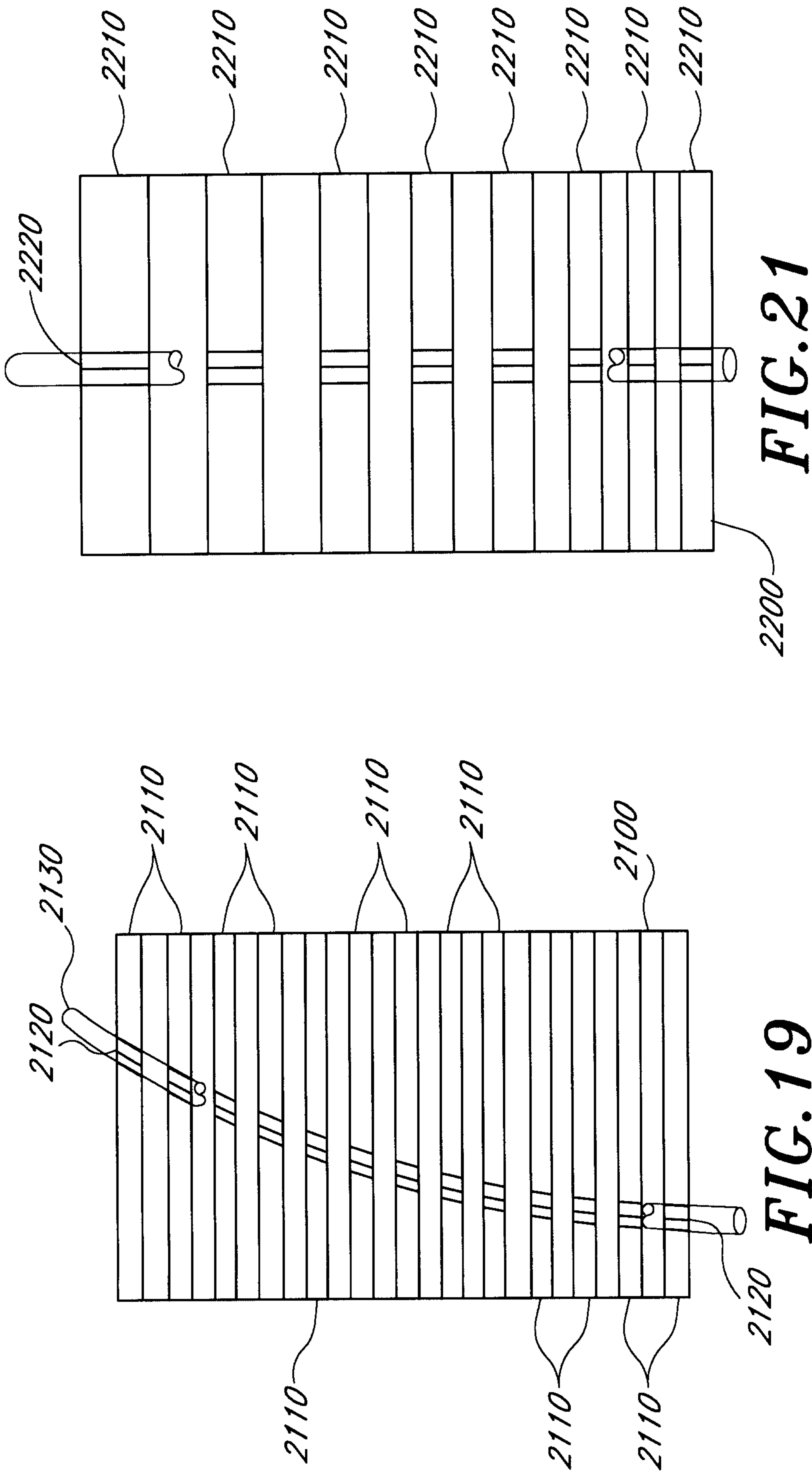


FIG. 18

FIG. 17



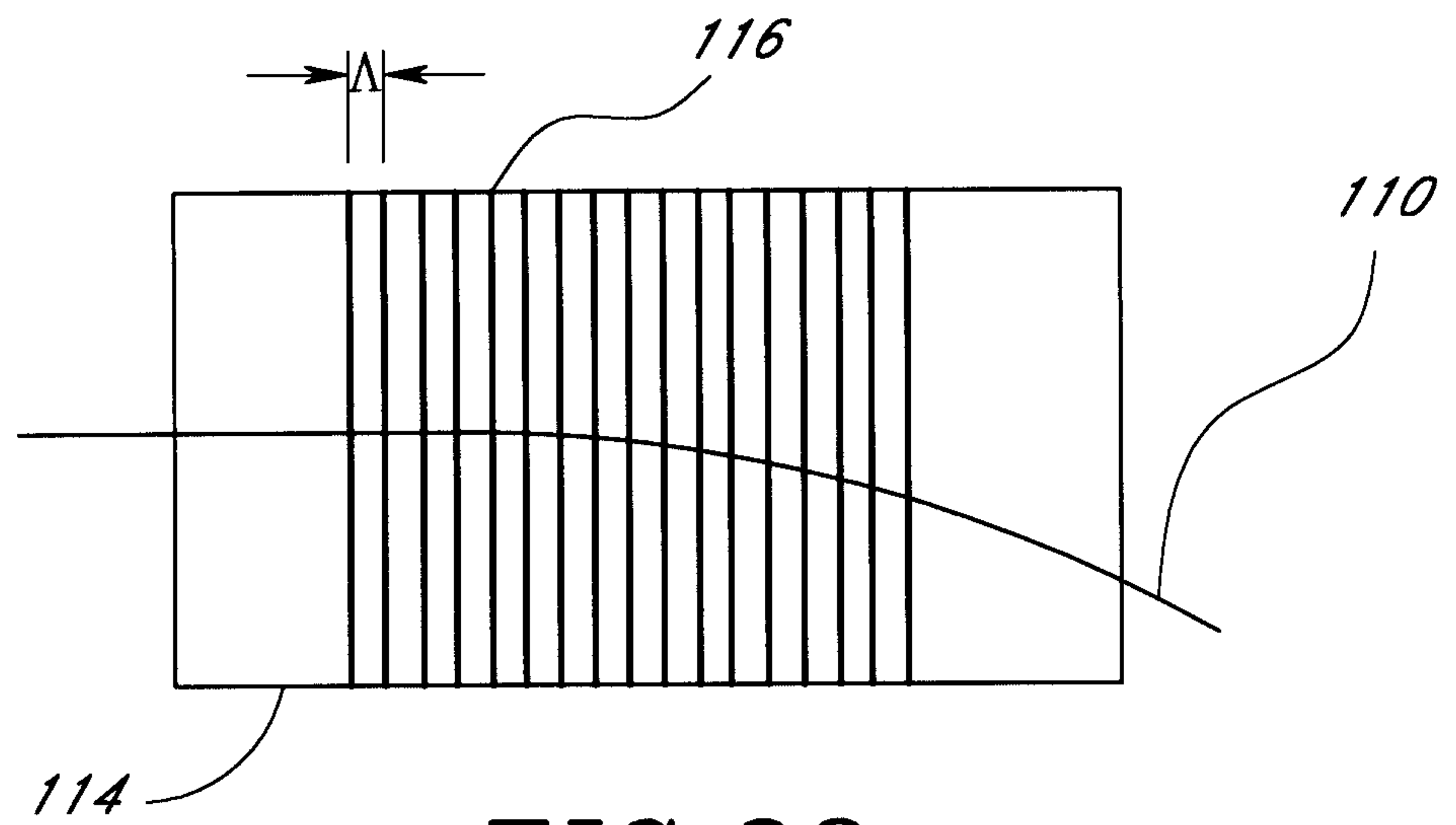


FIG. 23

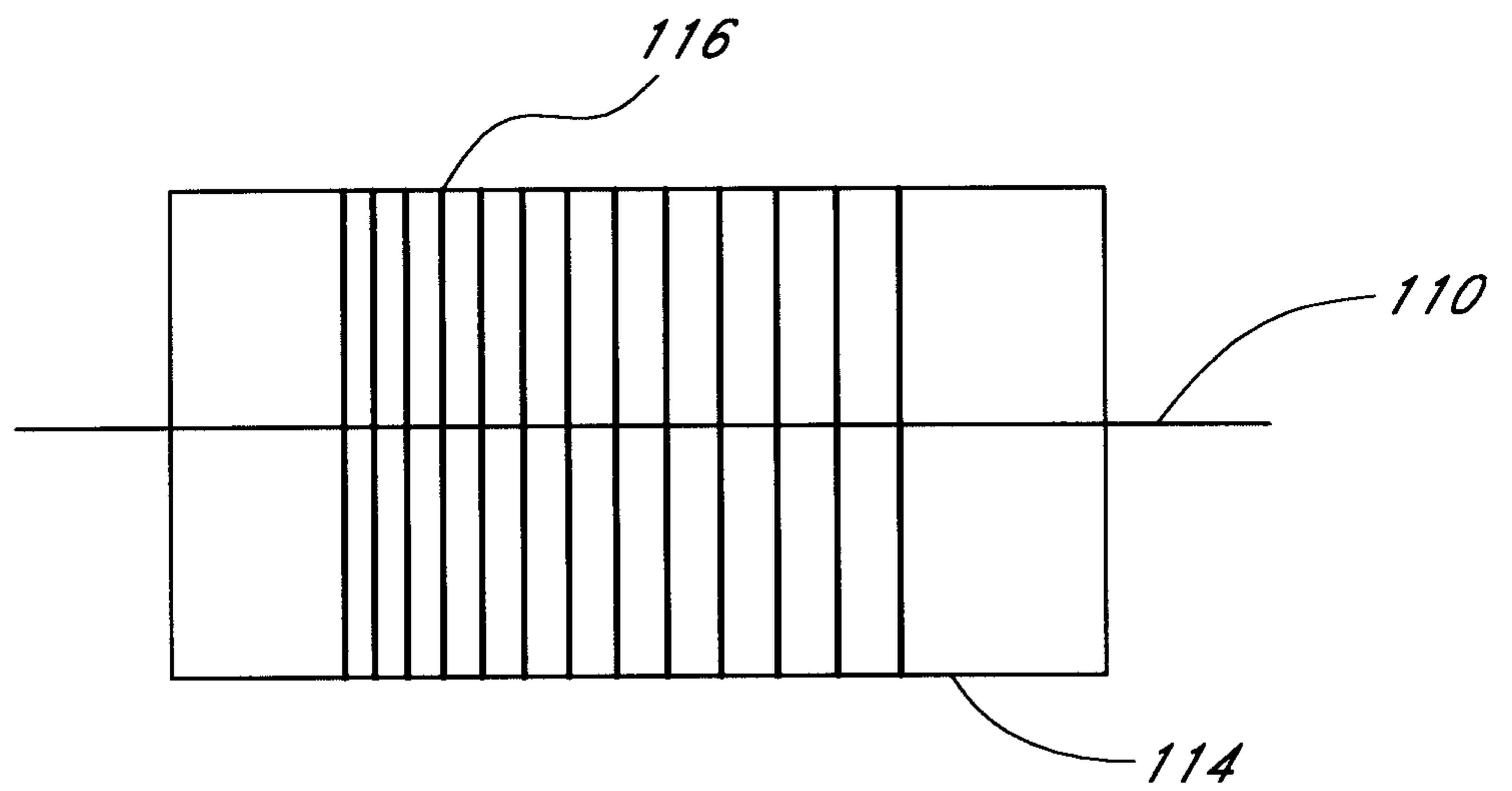


FIG. 24

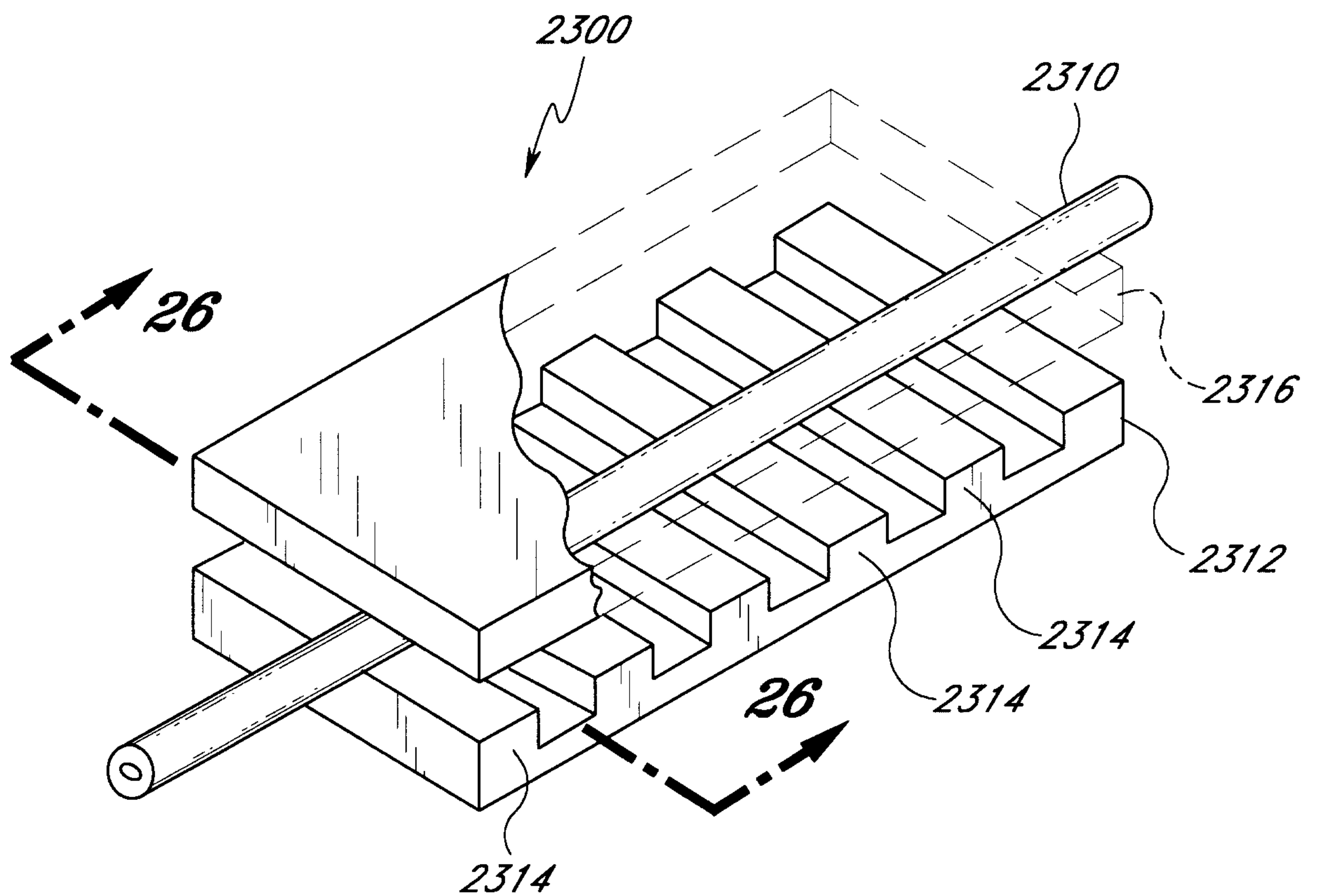


FIG. 25

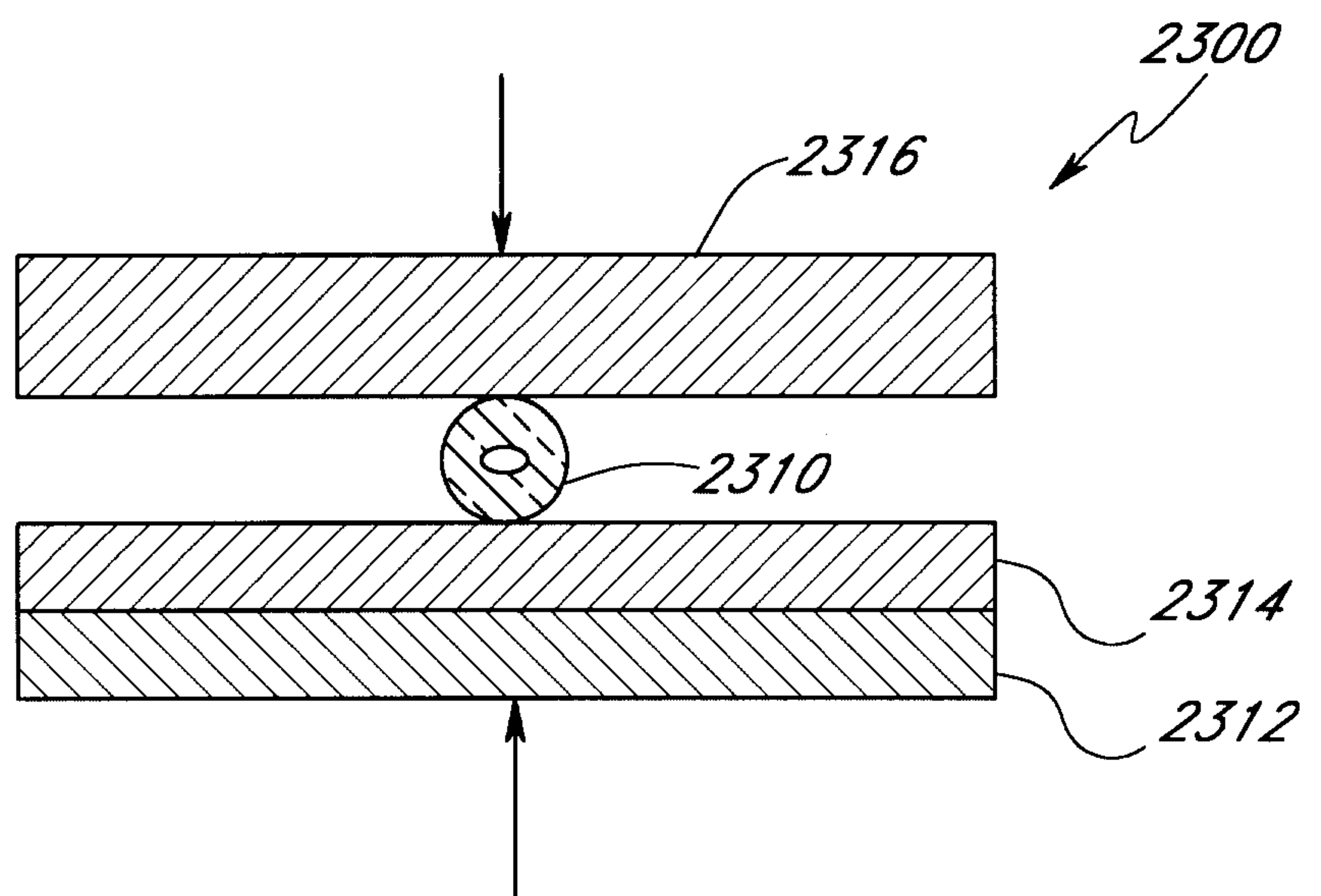


FIG. 26

