Office de la Propriété
Intellectuelle
du Canada

Un organisme
d'Industrie Canada

Canadian
Intellectual Property
Office

An agency of
Industry Canada

CA 2248042 C 2002/04/23

(11)(21) 2 248 042

(12) BREVET CANADIEN
CANADIAN PATENT

(13) C

(86) Date de dépôt PCT/PCT Filing Date: 1997/03/24
(87) Date publication PCT/PCT Publication Date: 1997/10/02
(45) Date de délivrance/Issue Date: 2002/04/23
(85) Entrée phase nationale/National Entry: 1998/09/03
(86) N° demande PCT/PCT Application No.: GB 1997/000817
(87) N° publication PCT/PCT Publication No.: 1997/036198
(30) Priorité/Priority: 1996/03/27 (96302115.9) EP

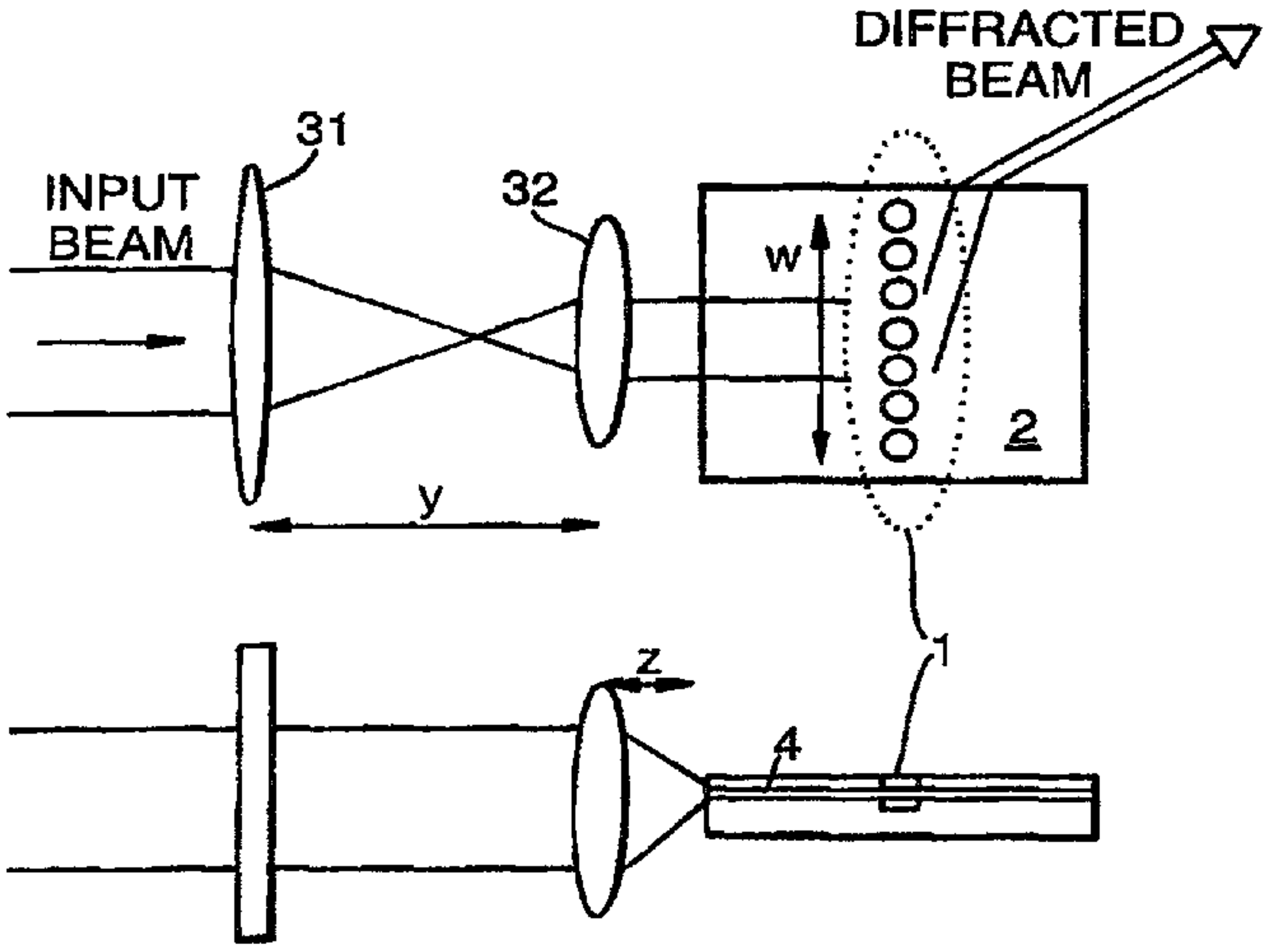
(51) Cl.Int.^{6}/Int.Cl.^{6} G02B 5/18, G02B 5/30, H04J 14/02

(72) **Inventeurs/Inventors:**
GRANT, Robert Sinton, GB;
BURT, Michael Graham, GB

(73) **Propriétaire/Owner:**
BRITISH TELECOMMUNICATIONS PUBLIC LIMITED COMPANY, GB

(74) **Agent:** GOWLING LAFLEUR HENDERSON LLP

(54) Titre : RESEAU DE DIFFRACTION OPTIQUE
(54) Title: OPTICAL DIFFRACTION GRATING



(57) Abrégé/Abstract:
An optical diffraction grating is formed from a region of photonic crystalline material (1). Light is coupled into the photonic crystalline material, and the grazingly emergent ouptut beam is collected. The photonic crystalline material may comprise an array of holes formed in a substrate (2) of dielectric material, e.g. InP, and integrated with planar waveguide structures (4).

PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
G02B 6/124, 6/293, 5/18, H01P 1/00

A1

(11) International Publication Number: **WO 97/36198**

(43) International Publication Date: 2 October 1997 (02.10.97)

(21) International Application Number: PCT/GB97/00817

(22) International Filing Date: 24 March 1997 (24.03.97)

(30) Priority Data:
96302115.9 27 March 1996 (27.03.96) EP
(34) Countries for which the regional or international application was filed: GB et al.

(71) Applicant *(for all designated States except US)*: BRITISH TELECOMMUNICATIONS PUBLIC LIMITED COMPANY [GB/GB]; 81 Newgate Street, London EC1A 7AJ (GB).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: BURT, Michael, Graham [GB/GB]; Glebe Corner, Kingston Road, Woodbridge, Suffolk IP12 4AY (GB). GRANT, Robert, Sinton [GB/GB]; 17 Sawyers, Elmsett, Ipswich, Suffolk IP7 6QH (GB).

(74) Agent: WELLS, David; BT Group Legal Services, Intellectual Property Dept., 8th floor, 120 Holborn, London EC1N 2TE (GB).

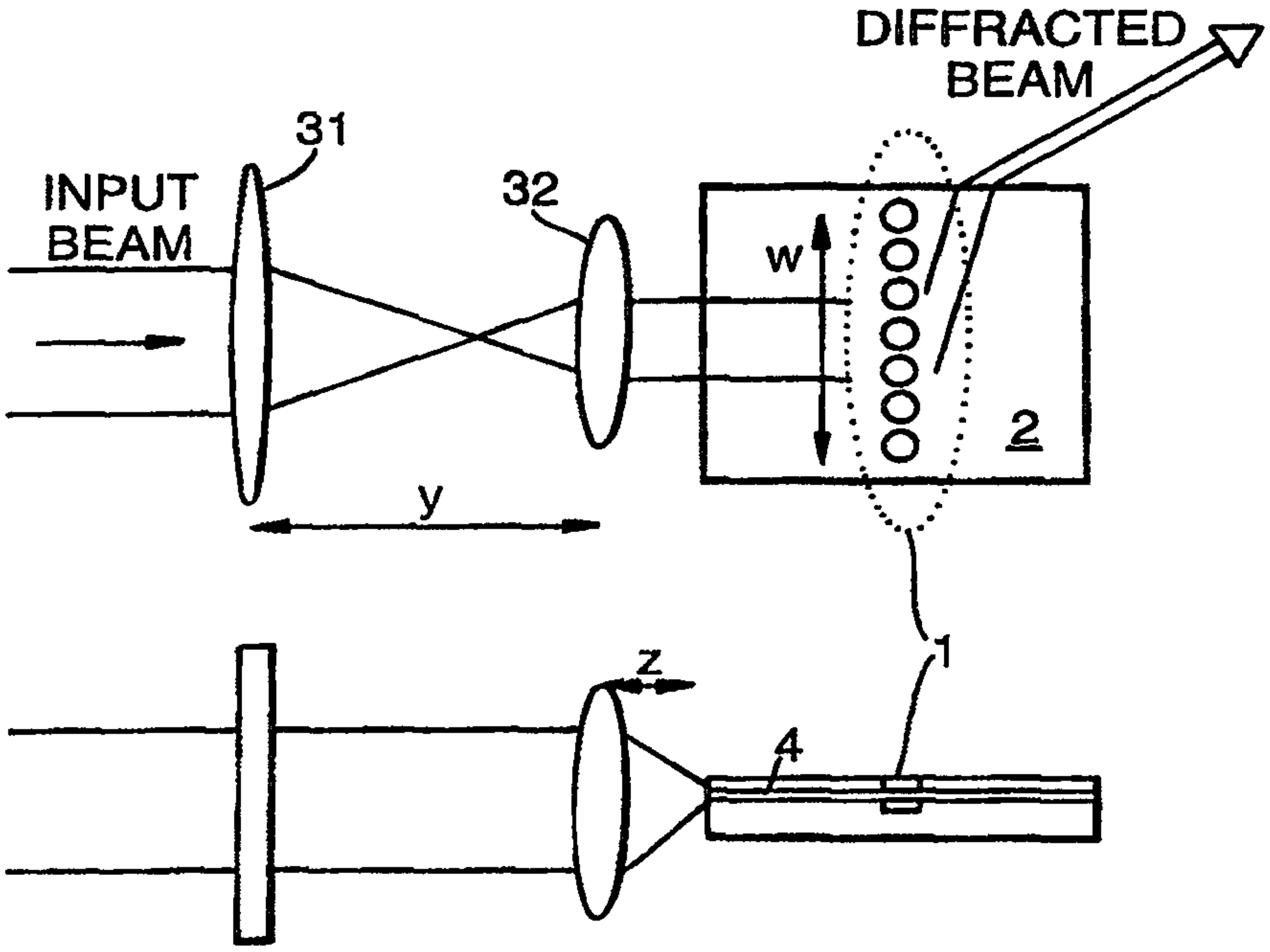
(81) Designated States: AU, CA, JP, NO, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: OPTICAL DIFFRACTION GRATING

(57) Abstract

An optical diffraction grating is formed from a region of photonic crystalline material (1). Light is coupled into the photonic crystalline material, and the grazingly emergent output beam is collected. The photonic crystalline material may comprise an array of holes formed in a substrate (2) of dielectric material, e.g. InP, and integrated with planar waveguide structures (4).



OPTICAL DIFFRACTION GRATING

The present invention relates to an optical device suitable for use, for example, as a wavelength multiplexer/demultiplexer in an optical telecommunications system.

BACKGROUND TO THE INVENTION

Bulk optic diffraction gratings are well known, and it has previously been proposed to use such gratings as passive multiplexers/demultiplexers in optical networks employing wavelength division multiplexing (WDM). The use of bulk-optic components tends however to result in high packaging and maintenance costs. Accordingly, while the use of such components might be feasible if wavelength multiplexing/demultiplexing was to be confined to a few core switches, bulk optic components are not suitable for more widespread use in a network. Current interest in WDM centres on its use in local access networks in combination with optical time division multiplexing (OTDM) for longer links in the network. There remains a need therefore for a grating which is sufficiently robust and inexpensive to be used in local access loops throughout a network, and possibly to be present in each subscriber terminal.

The paper by Poguntke and Soole, "Design of A Multistripe Array Grating Integrated Cavity (MAGIC) Laser", Journal of Light Wave Technology, Vol. 11 No. 12 December 1993, discloses a grating formed in an InP-based planar waveguide structure. The grating is defined using photolithography and dry etched using, for example, chemically assisted ion-beam etching, to form a stepped wall extending perpendicularly through the planar waveguide. The grating is then metallised in order to improve its reflectivity. This structure, however, offers only limited angular dispersion, and so is not able to accommodate many wavelength channels without becoming unacceptably large.

SUMMARY OF THE INVENTION

According to the present invention, there is provided an optical device which includes:

a) an optical diffraction grating,

b) an optical input channel aligned to direct optical radiation onto the waveguide for diffraction, and

c) one or more optical output channels the or each of which is aligned to acquire optical radiation diffracted by the diffraction grating;

wherein:

i) said device comprises a waveguiding layer located between and in contact with a first confining layer and a second confining layer,

ii) the grating is located in the central layer, and

iii) the grating takes the form of a planar array of scattering centres said array having 1 - 10 rows of scattering centres.

In preferred embodiments of the invention, the array has 1, 2 or 3 rows of scattering centres. A single row of scattering centres may advantageously be employed. Each scattering centre preferably takes the form of a hole in the central layer. Each hole preferably contains a material responsive to an electric field, e.g. a liquid crystal. Each hole also preferably extends through the first covering layer, through the central layer and into the second covering layer, each hole containing filler material having a refractive index which is different from the refractive index of the rest of the central layer. The central layer is preferably formed of III/V semiconductor and each hole contains a different III/V semiconductor. The first confining layer and the second confining layer are preferably formed of InP, the central layer is formed of InGaAsP and each hole contains either InP or GaInAs.

The input channel referred to above preferably includes a waveguide formed in the central layer and the or each output channel typically includes a waveguide formed in the central layer.

Preferred embodiments of the invention also include two or three rows of scattering centres and the spacing between the rows is such that, at a predetermined wavelength of operation, the grazingly emergent beam scattered from one row interferes constructively with the grazingly emergent beam scattered from the or each other row.

The term photonic crystalline material as used in the description of embodiments following denotes a material manufactured with a periodic variation in refractive index, having a periodicity of the order of magnitude of an optical wavelength. As further discussed below, such material is sometimes referred to as “photonic band gap material”.

The described embodiments use photonic crystalline material to provide a grating suitable for integration with other optical components and exhibiting high dispersion and efficiency. Photonic crystals are a class of material manufactured with a periodic dielectric structure. The behaviour of photons within such a structure is found to be analogous to that of electrons within a semiconductor. In particular it is found that there are photonic band gaps (PBGs) analogous to electronic band gaps in semiconductor crystals. Photons having wavelengths within the band gap range are forbidden to propagate. Most work on photonic crystals has focused on producing these photonic band gaps. However, a novel analysis by the present inventor has shown that photonic crystals exhibit another property which can be exploited to provide a highly efficient grating. It is found that if the pitch of the photonic crystal is selected so that the first order diffracted beam is grazingly emergent from the crystal, then the diffracted angle varies sharply with wavelength, while the diffracted beam has a relatively high output intensity, potentially equal to 20% or more of the input optical intensity.

Preferably the region of photonic crystalline material is generally planar. The photonic crystalline material may comprise a generally regular array of scattering centres formed in a dielectric material, in which case preferably the array is a minimal array no more than 10 rows deep and preferably only 1, 2 or 3 rows deep. The scattering centres may comprise holes formed in a dielectric substrate.

While work on photonic band gap materials has previously aimed at producing extensive 3-dimensional arrays, the present inventor has found that an effective diffraction grating can be formed from an array which is only a few rows deep and which may comprise just a single row. Where 2 or more rows are present, then preferably the spacing between the rows is such that, at a predetermined wavelength of operation, the grazingly emergent beam scattered from one row interferes constructively with the grazingly emergent beam scattered from the or each other row.

When the separation between rows is chosen so that in a preferred scattering direction there is constructive interference, then the grating functions as a highly efficient fixed frequency filter and as such is particular valuable for use in WDM systems.

Preferably the means for coupling light to and from the photonic crystalline material include waveguides formed on a common substrate with the photonic crystalline material. The waveguides may comprise planar structures, and may be arranged to confine light in the direction normal to the planar surface. It is particularly preferred that the waveguide should be a ridge waveguide arranged also to confine the beam in the plane parallel to the planar surface. The grating may be arranged to operate transmissively, with the waveguide for the input beam on one side of the photonic crystalline material, and the waveguide for the output beam on the other side of the photonic crystalline material.

Alternatively, the grating may be arranged to function reflectively, in which case the means for coupling the input beams and the means for coupling the grazingly emergent output beam are located on the same side of the photonic crystalline material.

Preferably the dielectric material is a III-V material, and more preferably is indium phosphide.

The photonic crystal may comprise a regular array formed from two dielectric materials of differing refractive indices. This structure may be formed as an array of holes in a first dielectric material with the holes filled with a second dielectric material. Alternatively, where the substrate includes, e.g., a quaternary waveguide layer, then the holes may be filled with the same material used to form the basis of the substrate. An alternative structure may comprise pillars of a first dielectric material extending into air or into a second dielectric material. One of the dielectric materials making up the photonic crystal may have a refractive index which is variable in response to an applied control signal. This may be an electro-optic material responsive to an applied electrical field, or a non-linear optical material responsive to an applied optical control signal.

The use of a material with a variable refractive index in the photonic crystal enables the grating to function as a tunable filter.

The diffraction grating described herein is not limited to use in configurations in which it is the grazingly emergent beam which is output. It may also be used, for example, in configurations in which the reflected beam is output, or in which a beam diffracted at a relatively larger angle is output.

The present invention also encompasses wavelength multiplexers and demultiplexers including a grating in accordance with the preceding aspects of the invention.

DESCRIPTION OF THE DRAWINGS

Devices and methods of manufacture embodying the present invention will now be described in further detail, by way of example only, with reference to the accompanying drawings in which:

Figures 1a and 1b are a plan and sectional side view respectively of a grating embodying the present invention;

Figure 2 is a diagram showing schematically the photonic crystal of the grating of Figure 1;

Figure 3 shows plots of reflection and transmission coefficients as a function of frequency for the photonic crystal of Figure 2;

Figures 4a and 4b are schematics of alternative photonic crystal microstructures;

Figure 5 is a cross-sectional view showing the structure of the planar substrate of the grating of Figure 1;

Figure 6 is a schematic of a second alternative photonic crystal;

Figures 7a and 7b are sectional and plan views of a third alternative photonic crystal;

Figures 8a and 8b are plots of reflection and transmission coefficients of further examples of gratings embodying the present invention;

Figures 9a and 9b are plan and sectional views of a WDM demultiplexer;

Figure 10 is a plan view of an alternative embodiment of a WDM multiplexer;

Figure 11 is a plot showing the polarisation dependence of reflection coefficients of a grating embodying the present invention; and

Figure 12 is a plot showing the ratio of the reflection coefficients of different polarisation states in the example of Figure 11.

DESCRIPTION OF EXAMPLES

A grating comprises a region of photonic crystalline material 1 formed in a multi-layered planar substrate 2. An optical system comprising a first lens 31 with a focal length of, e.g. 10cm, and a second lens 32 with a focal length of, e.g. 1cm collimates an input optical beam. The lenses 31,32 are separated by a distance y which is equal to the sum of the focal lengths. The lens 32 is spaced from a facet of the planar substrate 2 by a distance z of 1 cm in this example. The optical system couples light into a waveguide layer 4 where it propagates to meet the photonic crystal 1 with normal incidence. A grazingly emergent diffracted beam is transmitted through the photonic crystal 1 and propagated through the waveguide layer 4 and emerges from a side facet of the planar substrate. The emergent beam tends to diverge in the direction normal to the planar substrate. Optionally a cylindrical lens may be used to collimate the emergent beam.

Figure 2 shows schematically the configuration of the photonic crystal 1. In this example, it comprises a linear array of holes formed in a substrate of dielectric constant 13 with a pitch of 0.57μm. As shown in the diagram, a normally incident input beam with a wavelength of around 1550 nm is diffracted by the photonic crystal to produce grazingly emergent transmitted and reflected beams. In addition, part of the beam passes straight through the photonic crystal without diffraction, and part is reflected. The width of the grating w is in this example 800 microns, the distance from the input fibre to the grating is 4mm and the distance from the grating to the output is 4mm. For ease of illustration, only a relatively few holes are shown in the Figure. In practice, as further discussed below, the array may comprise a row of 1000 or more holes.

Figure 3 shows the reflection and transmission coefficient for the normally incident beam as a function of frequency normalised to 1.55µm. Plot a is the transmission coefficient, b is the reflection coefficient and plots c and d are the coefficients of the transmitted and reflected diffracted beams respectively. The onset of grazing emergence is seen in plots c and d at a normalised frequency of around 0.8 and is marked by the dashed line. As set out in the theoretical analysis below, it is found that the grazingly emergent beam at angles of a few degrees, say 3 to 5 degrees, has a practically useful level of optical power and emerges at an angle which varies rapidly with wavelength.

As an alternative to use with a normally incident beam, the grating may be used with a beam incident at an angle of, e.g., 30 degrees. Plot 3b shows the reflection coeffiecients in this case. In this case the grazingly emergent output beam for a given wavelength will have different diffraction angles on either side of the normal to the plane of the photonic crystal.

The pitch and hole size of the array, and the angle of incidence, may be varied according to the refractive index of the substrate material and the desired wavelength range in which the grating is to be used. Figures 8a and 8b are graphs showing the performance of gratings constructed with different pitches and angles of incidence. Figure 8a is for a grating with a pitch of 0.47 microns used at normal incidence. Figure 8b relates to a grating with a pitch of 0.313 microns used with a beam incident at an angle of 30 degrees to the normal. The hole radius in each case is 0.17 microns in 8a and 0.1175 microns in 8b. In both cases, the dielectric constant of the substrate is 10.9, giving a refractive index of 3.3.

The holes need not have a circular cross section and may, for example, have a cross section which is generally square.

In the present examples, the array of holes making up the photonic crystal are produced by reactive ion-beam etching (RIE) in a planar InP substrate. Figure 5 shows in detail the structure of the planar substrate.

The process of manufacture can be broken down into two stages: an epitaxy or deposition stage, and a subsequent stage in which the microstructure is etched. In the first stage, a waveguiding layer is fabricated on InP semiconductor material by a series of epitaxial depositions using the Metal-Organic Vapour Phase Epitaxy (MOVPE) technique. This first stage includes the following steps:

1. A buffer layer of 1000nm thickness of InP is deposited;
2. A waveguiding layer 300nm thick of InGaAsP is deposited - the composition of the InGaAsP is such that it has a bandgap wavelength of approximately 1.3 microns;
3. A cladding layer 300nm thick of InP is deposited.

All the deposited materials are nominally pure, i.e. undoped.

Subsequently, in the second stage, microstructures are etched into the wafer. This is done using reactive ion etching. Direct write technology is used to create the mask directly on the sample. The second stage involves the following steps:

1. The sample is briefly cleaned in acid and then a 100nm thick layer of silicon nitride Si_3N_4 is deposited.
2. A layer of photoresist which is known as "ebeam resist" and which is sensitive to an electron beam is spun onto the sample to a thickness of approximately 500nm. In this case, the resist used is that manufactured by Nippon Zeon and known as ZEP520.*
3. The resist is exposed in the desired microstructure pattern using electron beam lithography.
4. The resist is then developed. This dissolves the exposed areas. The unexposed ZEP520 remains and forms a mask which is used in the following stages.
5. Reactive ion etching using CF_4 etches into the silicon nitride layer. This transfers the the mask pattern from the resist layer to the silicon nitride layer.
6. The sample is cleaned in two stages. The unexposed resist is removed, and then the polymer which results from the RIE process is removed.
7. The main RIE process is carried out. The patterned silicon nitride layer acts as a mask. The etching mixture consists of methane/hydrogen/oxygen. This mixture preferentially etches the InP/InGaAsP material over the silicon nitride mask.
8. The polymer resulting from the RIE process of step 7 is removed.

* Trademark

9. The sample is thinned from approximately 0.5mm thickness to approximately 150 microns thickness. This makes possible easier cleaving of individual samples. The individual samples are nominally 1x1 mm^2. The grating microstructure bisects the samples parallel to the sides.

It will be understood that the above process is described by way of example only, and that a variety of other processes may be used. For example, methane/hydrogen RIE may also be used. The etching may be followed by regrowth to fill the holes with a second dielectric material having a different refractive index to the substrate. Figure 6 is a schematic of a photonic crystalline region formed in this manner. In this example, the holes in the waveguide are filled with a III-V semiconductor material such as InP itself, or a ternary e.g. GaInAs. The material used to fill the holes may have a refractive index which is variable in response to an applied control signal. For example, it may comprise a liquid crystal material. The refractive index of the fill material then varies in response to a control voltage applied to a gate overlying the photonic crystal, allowing the grating to be tuned to a desired wavelength. Alternatively, the fill material may be, e.g., a semiconductor chosen to have a strong optical non-linearity. In this case its refractive index is controlled in response to an applied optical control signal.

Figures 7a and 7b show a further alternative structure for the photonic crystal. In this example, the scattering centres are pillars 71 of the substrate structure, extending into air. This structure may be produced by an RIE process as described above for the first example. The process is modified in that prior to the etching step, the silicon nitride photoresist is exposed everywhere except in the regions which are to form pillars. Then in the etching step, in the region 72 around the pillars the substrate is removed down to a depth of e.g. 0.7 microns leaving the pillars free-standing in a narrow trough in the substrate. It should be noted that although in this example the pillars, and in previous examples the holes, have had a circular cross-section, this is not essential for the functioning of the grating, and that scattering centres having other less uniform shapes may be used. For example the cross-section may be generally ellipsoid, and may vary in size at different depths through the hole or pillar. This allows the use of etching processes which may not produce perfectly regular shapes.

The present invention is by no means limited to the use of photonic crystals in the form of one-dimensional arrays as in this first example. Figure 4a shows schematically an example using 2 rows of holes, with the separation between the rows selected so that the path difference δ is equal to an integer number of wavelengths, giving constructive interference of the diffracted beam for the design wavelength. This constraint can be expressed algebraically as $\lambda = b(1-\sin(90-\phi))$ where b is the separation between the rows and ϕ is the diffraction angle. It can been seen that the use of two more rows has the effect of adding a preferred direction to the diffraction. That is, while the simple 1-dimensional array either transmits or reflects the diffracted order, the modified 2-dimensional structure reinforces either the reflected or the transmitted order, depending on the distance b. A structure formed in this way functions as a fixed wavelength filter.

For the 1-dimensional structure there is also a constraint on the array pitch, wavelength and diffracted angle of the form $\lambda = a \cos \phi$. Where a 2-dimensional structure is used, so that the constraint of the first equation above also applies, then there is a solution only for a single wavelength. The 2-dimensional structure can therefore be engineered to act as a fixed filter for one particular wavelength. The use of multiple rows of scattering centres is particularly preferred when the scattering centres are relatively weak in effect. This is the case if, for example, the holes etched in the substrate are relatively shallow and stop short of the waveguide layer or if they are filled with a second dielectric material having a refractive index close to that of the substrate. In this case more than a minimal array of holes may be required to produce a diffracted beam of sufficient power, and the array may be, for example, 10 or 15 rows deep.

Figure 4b shows an example of a lattice which is 6 rows deep. This 2-D lattice has two main sets of parallel planes, one running vertically and the other running approximately horizontally. The lattice is designed to obtain non-zero order diffraction from one set of planes, and zeroth order diffraction from the other set. The condition is applied that both sets of planes should give rise to diffraction in the same direction. Therefore to obtain zero order diffraction (specular reflection), the planes running approximately horizontally should be angled such that their normal bisects the angle between the input beam and the output beam. The spacing of these planes is not critical, but it can be advantageous to space them so that the microstructures along the planes have a separation sufficiently small that only zero order diffraction results. The planes running approximately horizontally have in general a separation less than the separation of the microstructures in the 1-D array considered originally. The following condition applies for first order diffraction:

$$\sin\theta + \sin\phi = n\lambda/d$$

where n is the order, λ is the wavelength, d is the separation of the planes or structures, and θ and ϕ are the angles of incidence of the incoming and outgoing beams. A structure which is formed in this way is not limited in operation to a single wavelength, but reinforces and diffracts different wavelengths through different angles. It is therefore suitable, for example, for use as a wavelength division mulitplexing (WDM) demultiplexer.

For the purposes of illustration, the above discussion treats the photonic crystal as comprising weak scattering centres, producing Bragg diffraction. In reality, the scattering centres in general produce strong scattering. The present inventor has carried out a novel analysis of a one-dimensional array of strong scattering centres, which is set out below.

The derivation of the dispersion equation for a planar photonic crystal will first be described. Let $\mathbf{k}_i$ and $\mathbf{k}_d$ be the wavevectors for the incident and diffracted waves and $\mathbf{g}$ a reciprocal lattice vector for the periodic variation of the refractive index which is the essential aspect of the grating. Because the electromagnetic fields that constitute the incident and diffracted waves must belong to the same irreducible representation of the group of translational symmetry operations for the grating, then

$$\mathbf{k}_d.\hat{\mathbf{g}} = (\mathbf{k}_i + \mathbf{g})\hat{\mathbf{g}} \qquad (1)$$

where $\hat{\mathbf{g}}$ is the unit vector along $\mathbf{g}$ ie parallel to the grating. Denoting by θ_i and θ_d the angles the incident and diffracted beams make with the normal to the grating and by $k = \frac{2\pi}{\lambda}$ the magnitude of the wavevector of the light (λ is the wavelength of the light in the medium either side of the grating) the equation (1) may be written $k\sin\theta_d = k\sin\theta_i + \frac{2\pi}{a}$ (2)

Claims:

1. An optical device which includes:
   - a) an optical diffraction grating,
   - b) an optical input channel aligned to direct optical radiation onto the waveguide for diffraction, and
   - c) one or more optical output channels the or each of which is aligned to acquire optical radiation diffracted by the diffraction grating;

wherein:

i) said device comprises a waveguiding layer located between and in contact with a first confining layer and a second confining layer,

ii) the grating is located in the central layer, and

iii) the grating takes the form of a planar array of scattering centres said array having 1 - 10 rows of scattering centres.

2. An optical device according to claim 1, wherein the array has 1, 2 or 3 rows of scattering centres.

3. An optical device according to claim 2, wherein each scattering centre takes the form of a hole in the central layer.

4. An optical device according to claim 3, wherein each hole extends through the first covering layer, through the central layer and into the second covering layer.

5. An optical device according to claim 3, wherein each hole contains filler material having a refractive index which is different from the refractive index of the rest of the central layer.

6. An optical device according to claim 5, wherein the central layer is formed of III/V semiconductor and each hole contains a different III/V semiconductor.

7. An optical device according to claim 6, wherein the first confining layer and the second confining layer are formed of InP, the central layer is formed of InGaAsP and each hole contains either InP or GaInAs.

8. An optical device according to claim 3, wherein each hole contains a material responsive to an electric field.

9. An optical device according to claim 8, wherein the material responsive to an electric field is a liquid crystal.

10. An optical device according to claim 1, wherein the input channel includes a waveguide formed in the central layer.

11. An optical device according to claim 1, wherein the or each output channel includes a waveguide formed in the central layer.

12. An optical device according to claim 2, wherein there are two or three rows of scattering centres and the spacing between the rows is such that, at a predetermined wavelength of operation, a grazingly emergent beam scattered from one row interferes constructively with a grazingly emergent beam scattered from the or each other row.

13. An optical device according to claim 2, wherein there is a single row of scattering centres.

Fig.1a

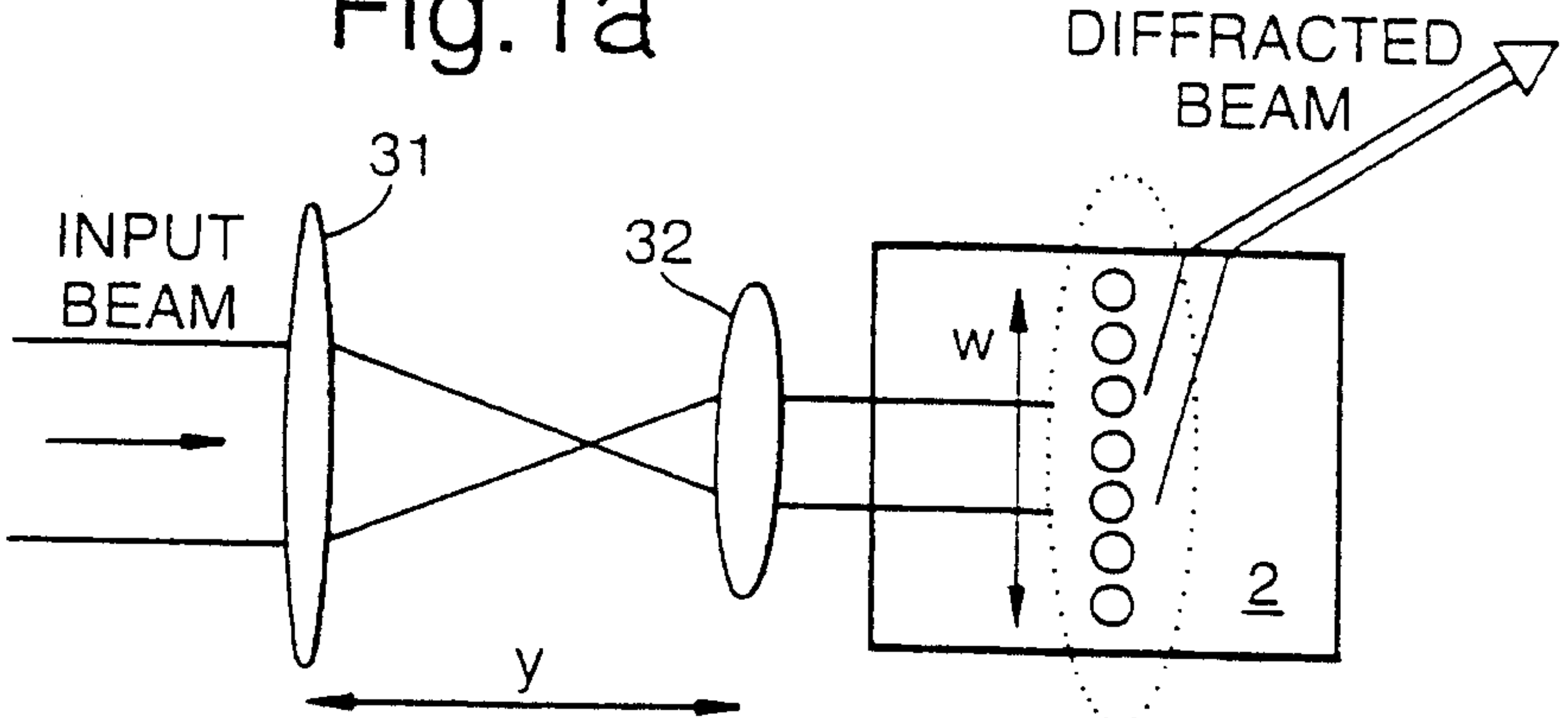


Fig.1b

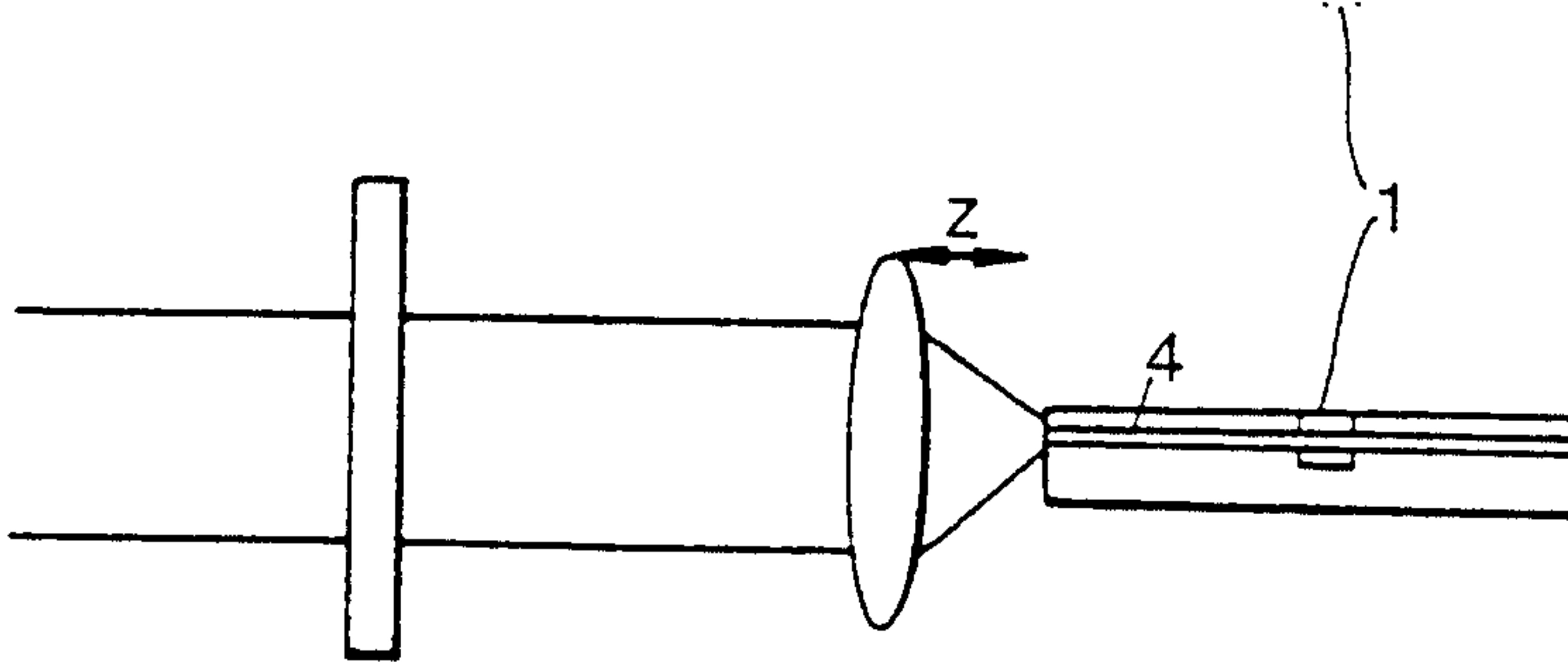


Fig.2.

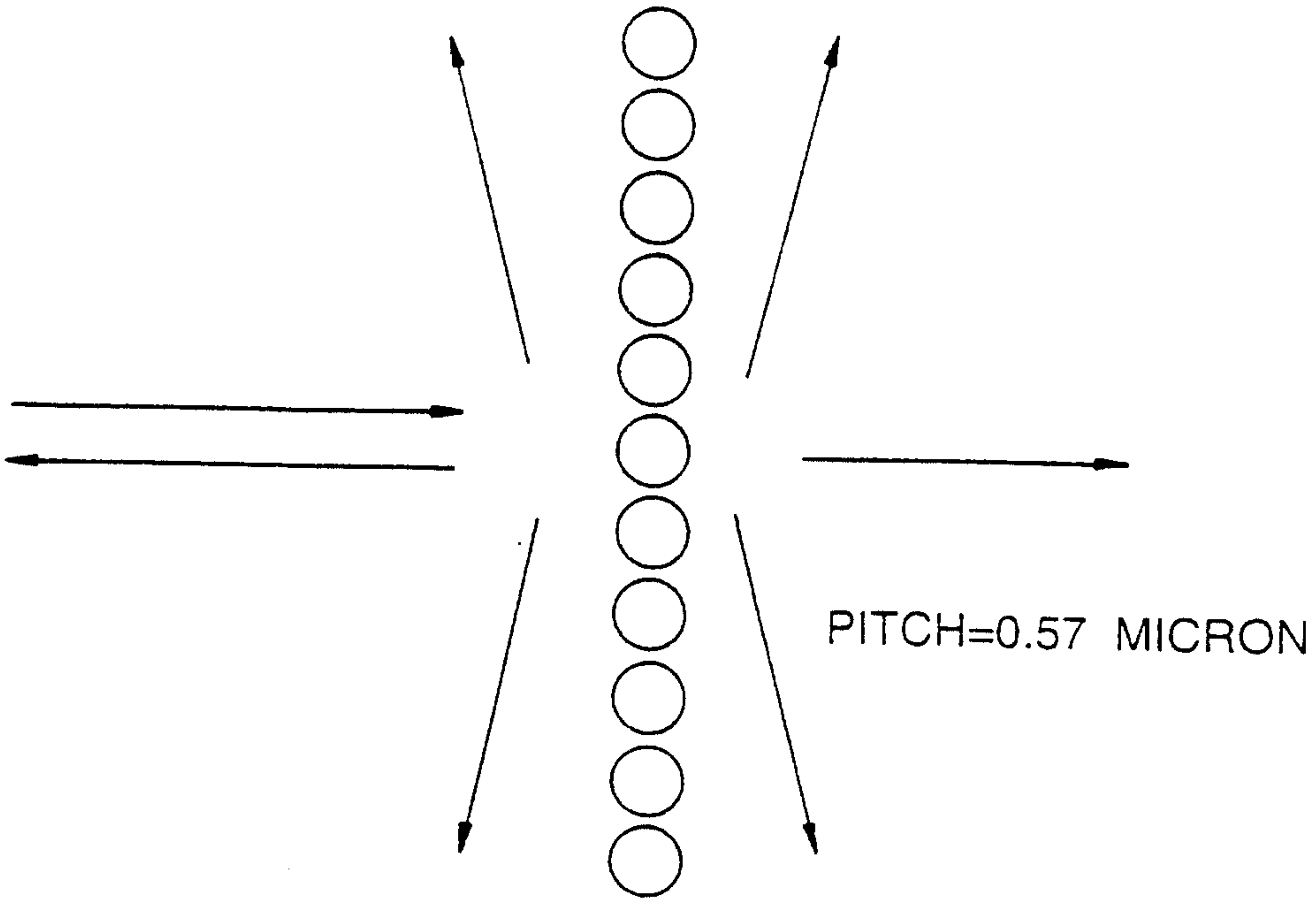


Fig.3.

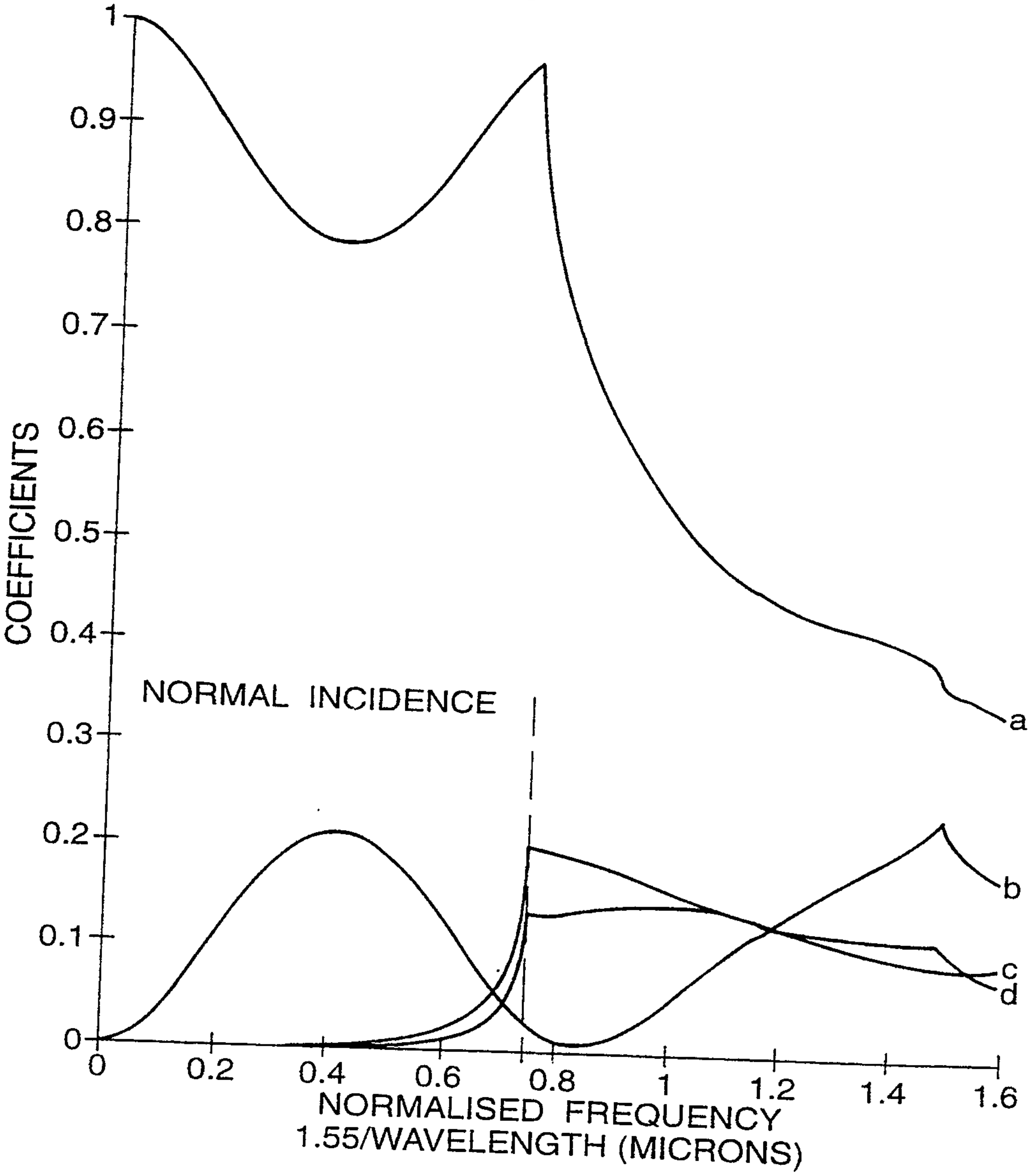

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
COEFFICIENTS
NORMAL INCIDENCE
a
b
c
d
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
NORMALISED FREQUENCY
1.55/WAVELENGTH (MICRONS)

Fig.4a.

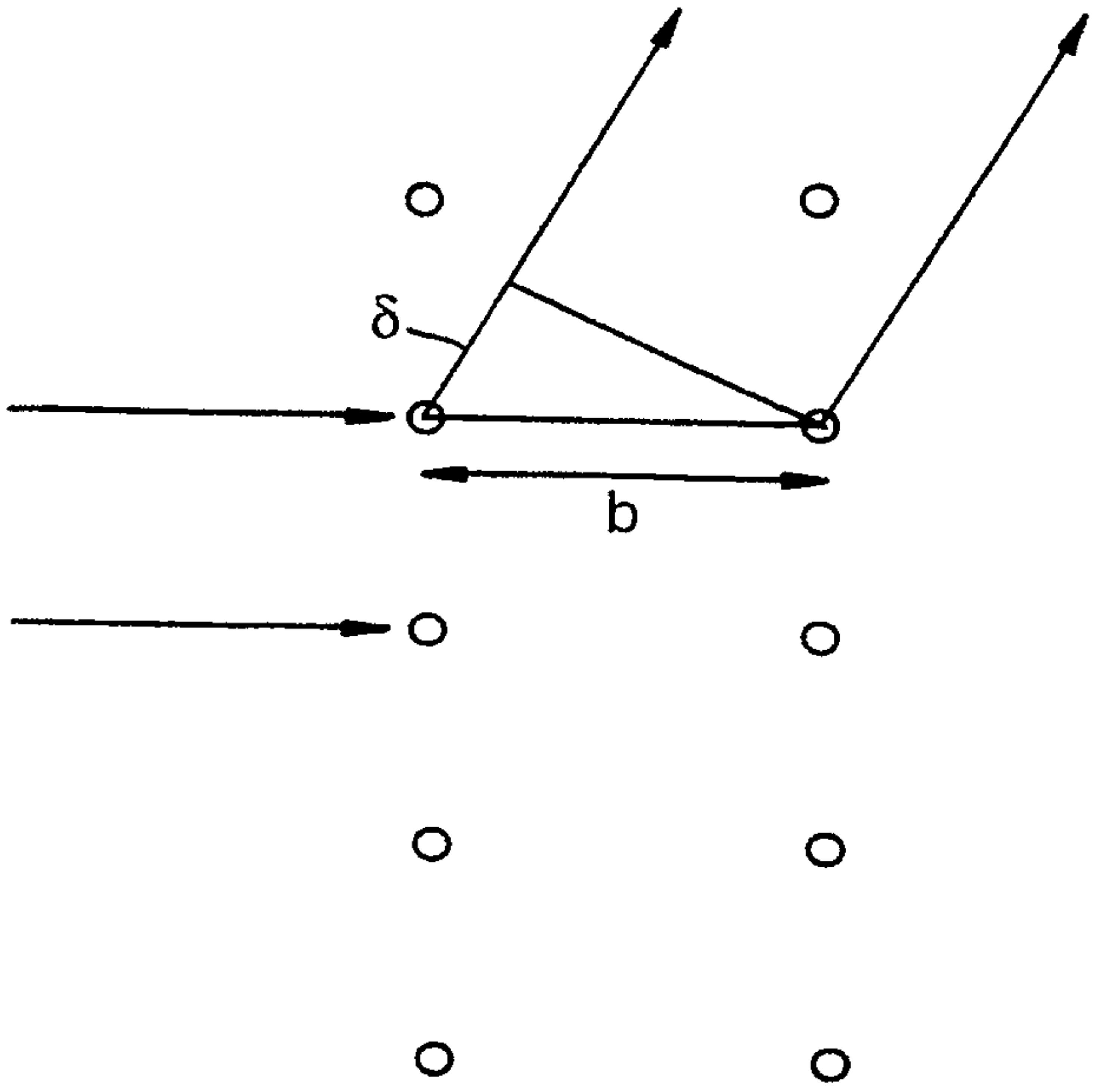

δ
b

Fig.4b.

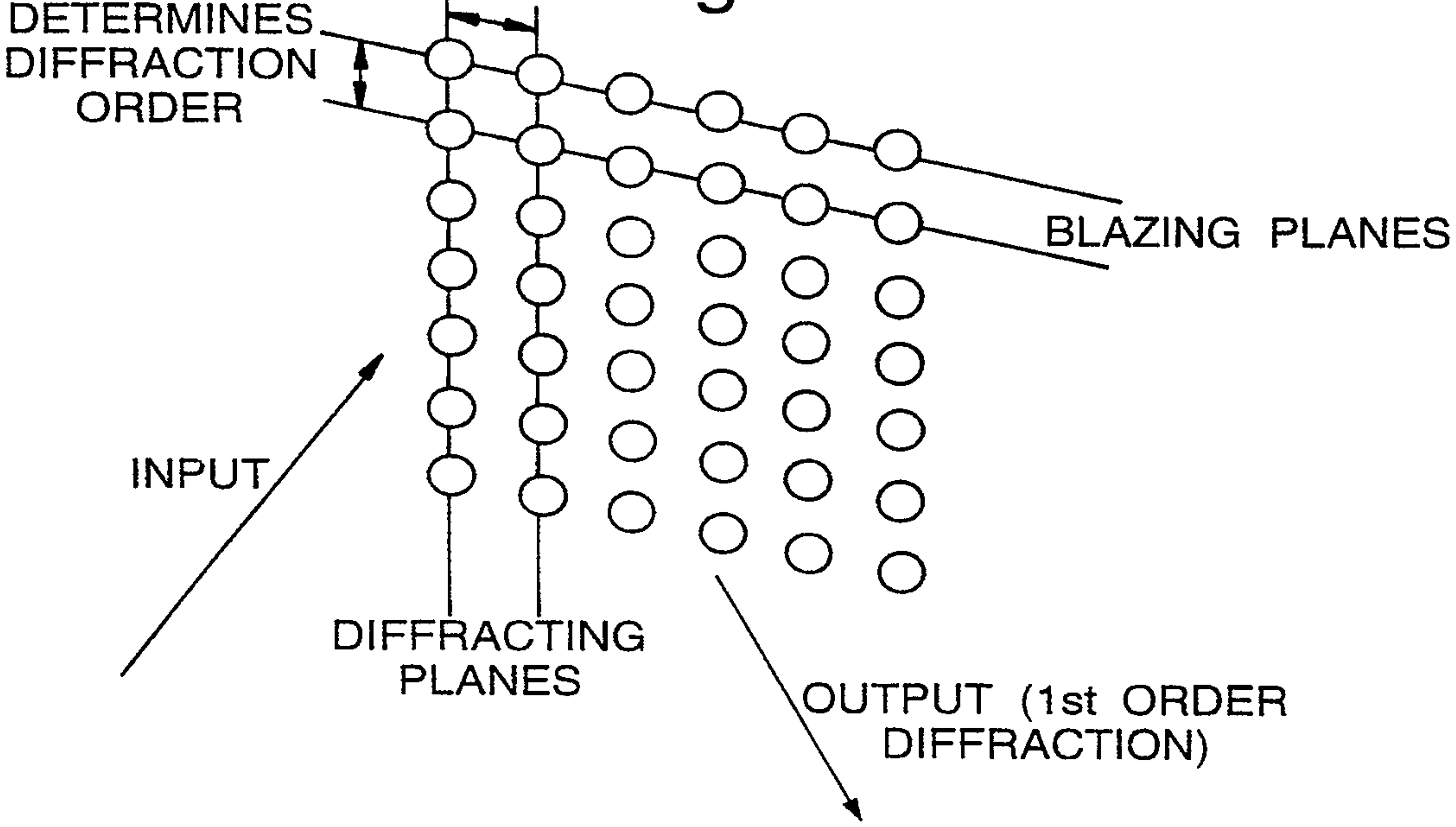

DETERMINES DIFFRACTION ORDER
BLAZING PLANES
INPUT
DIFFRACTING PLANES
OUTPUT (1st ORDER DIFFRACTION)

Fig.5.

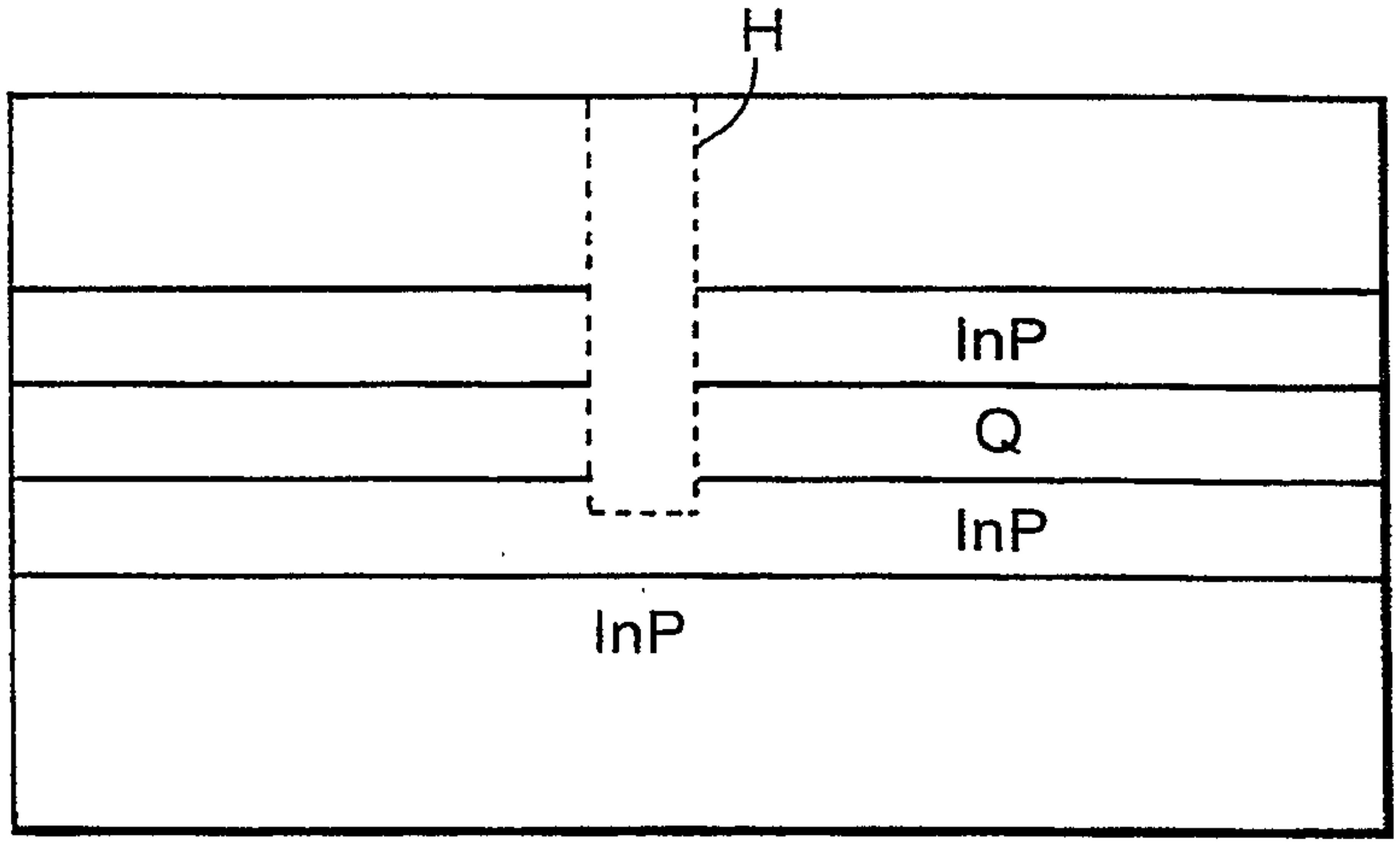


Fig.6.

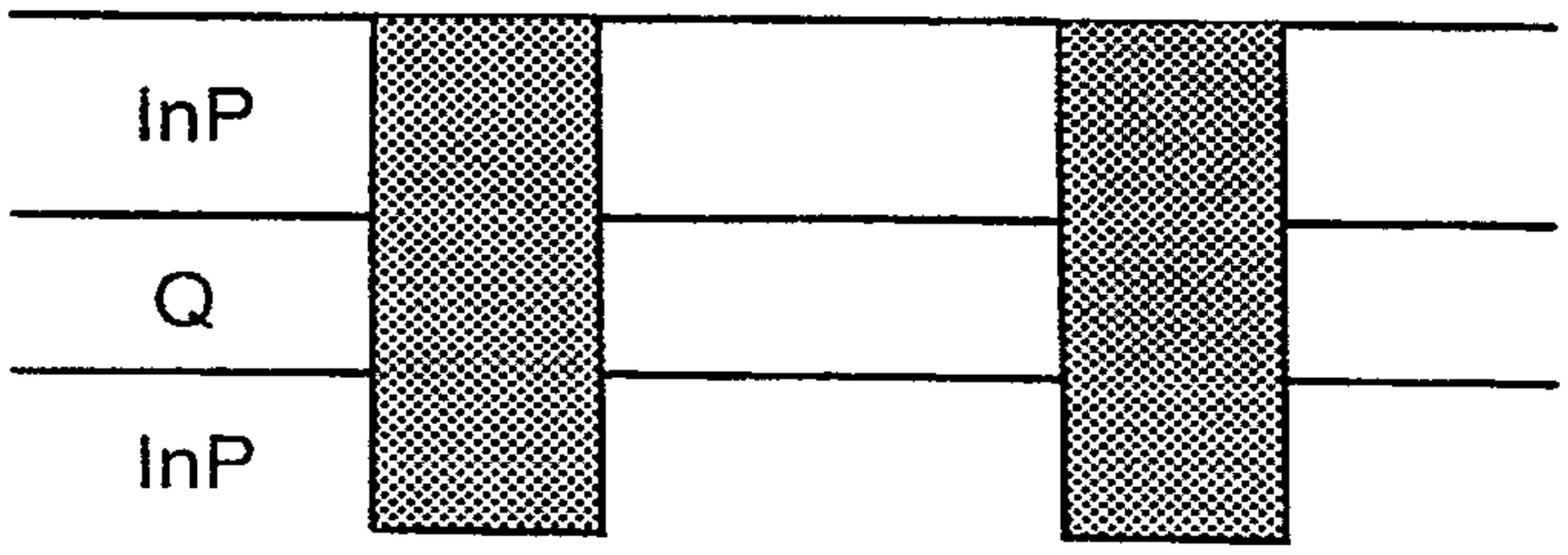


Fig.10.

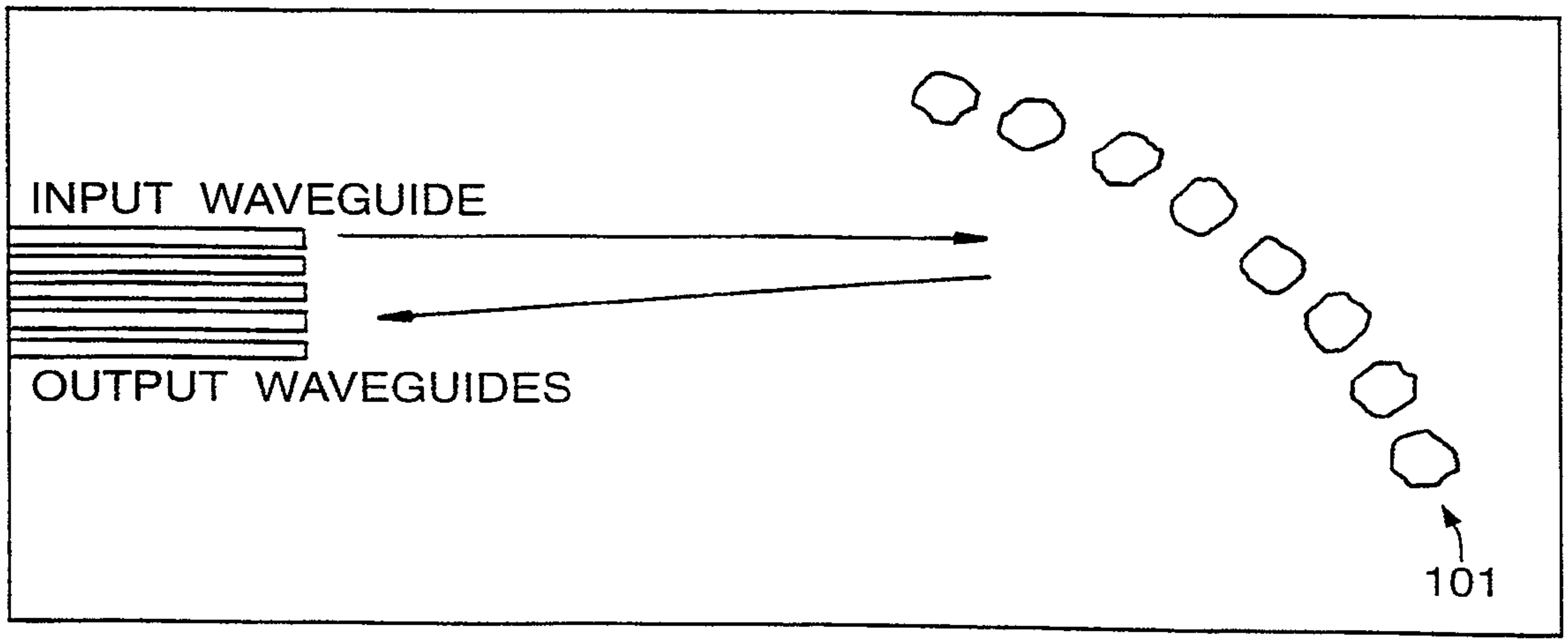


Fig.7a.

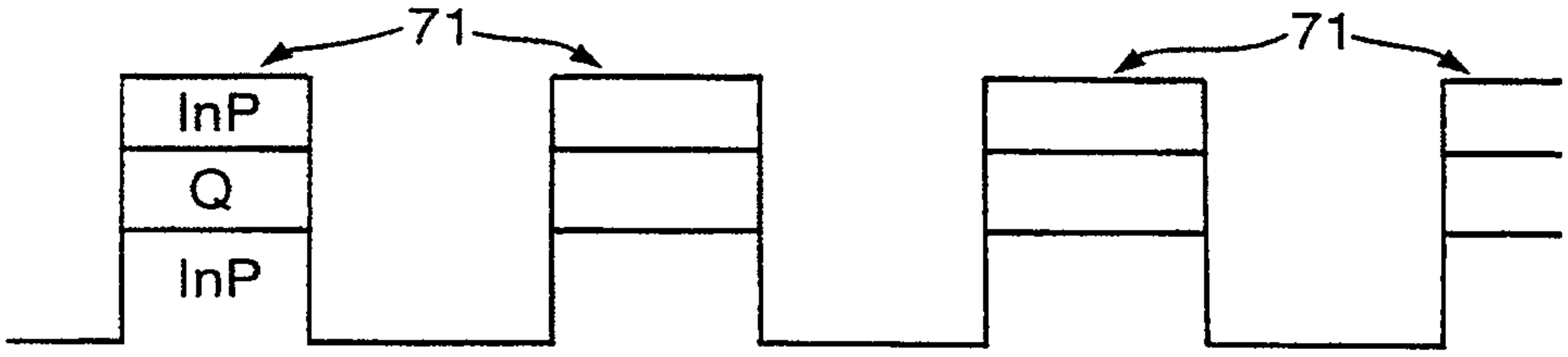


Fig.7b.

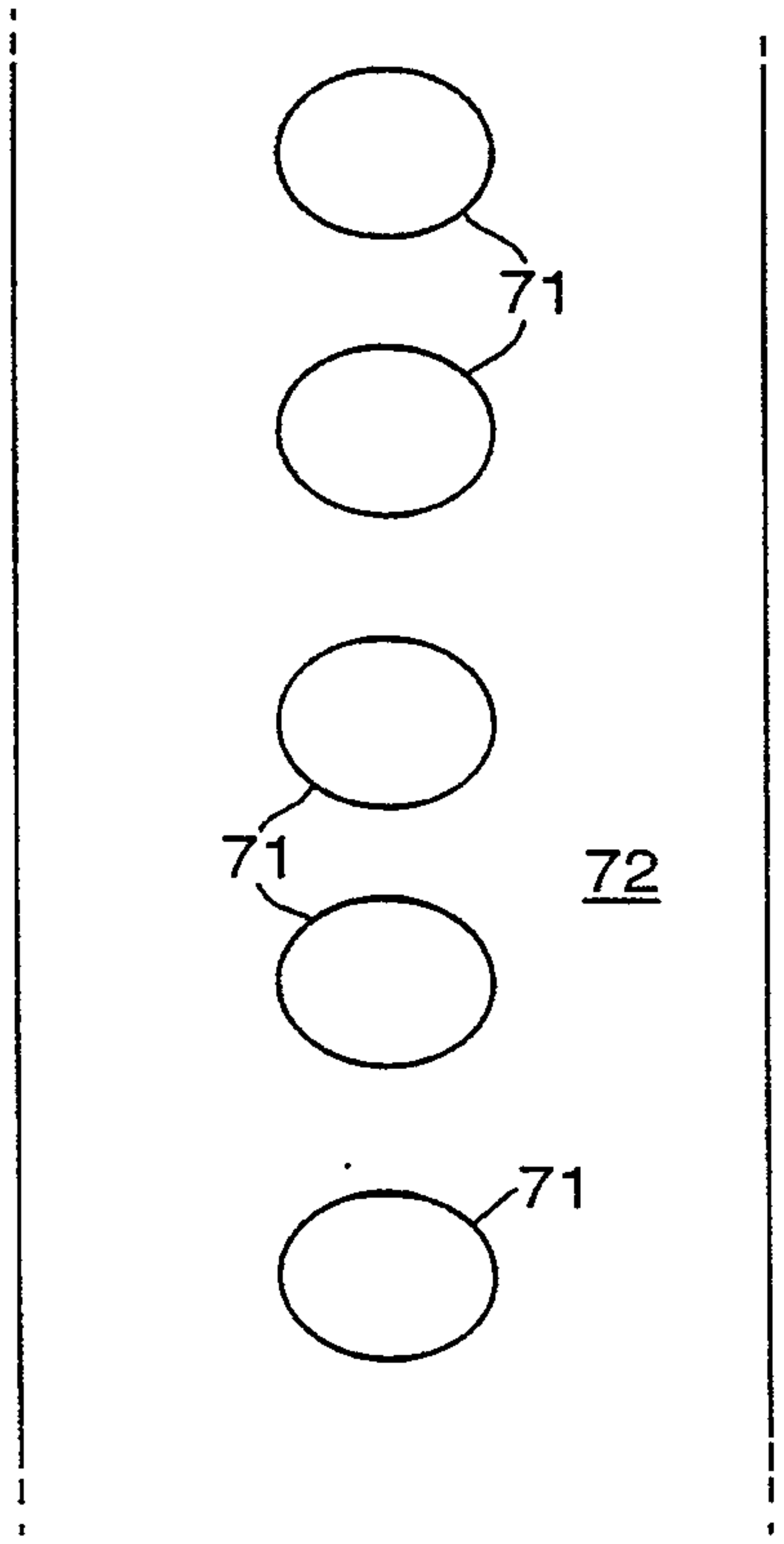


Fig.8a.

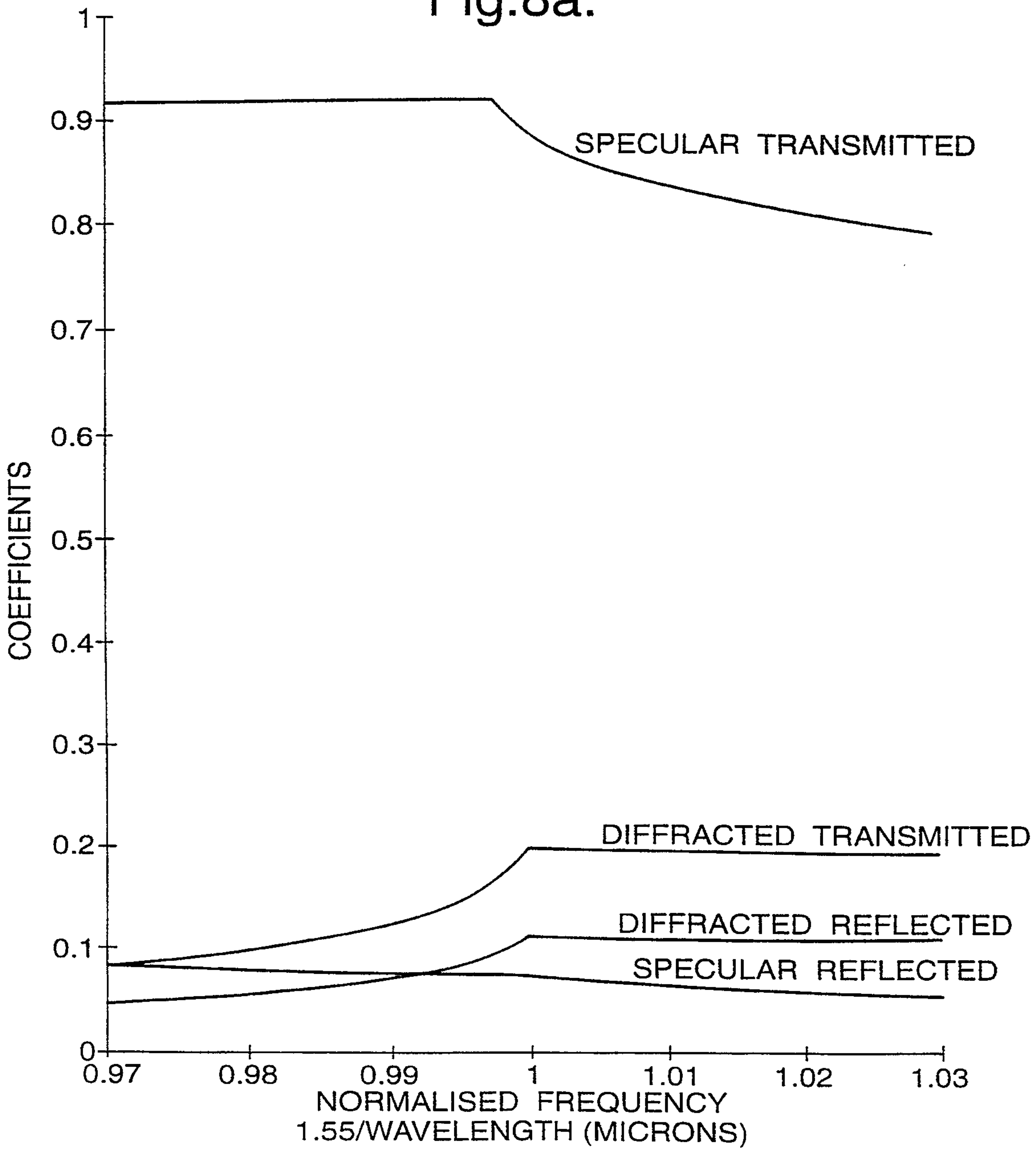

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
COEFFICIENTS
SPECULAR TRANSMITTED
DIFFRACTED TRANSMITTED
DIFFRACTED REFLECTED
SPECULAR REFLECTED
0.97
0.98
0.99
1
1.01
1.02
1.03
NORMALISED FREQUENCY
1.55/WAVELENGTH (MICRONS)

Fig.8b.

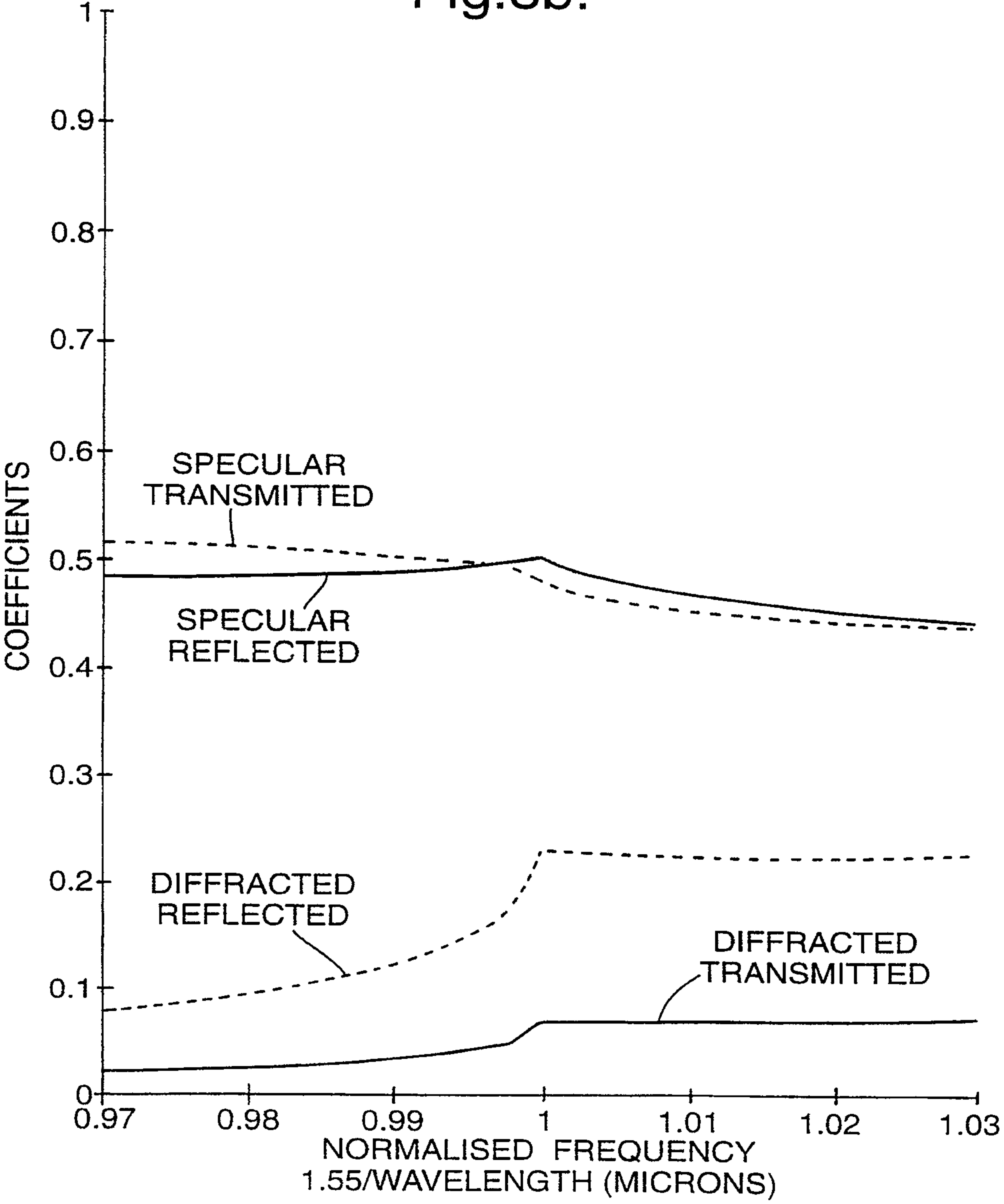

COEFFICIENTS
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
SPECULAR TRANSMITTED
SPECULAR REFLECTED
DIFFRACTED REFLECTED
DIFFRACTED TRANSMITTED
0.97
0.98
0.99
1
1.01
1.02
1.03
NORMALISED FREQUENCY
1.55/WAVELENGTH (MICRONS)

Fig.9a.

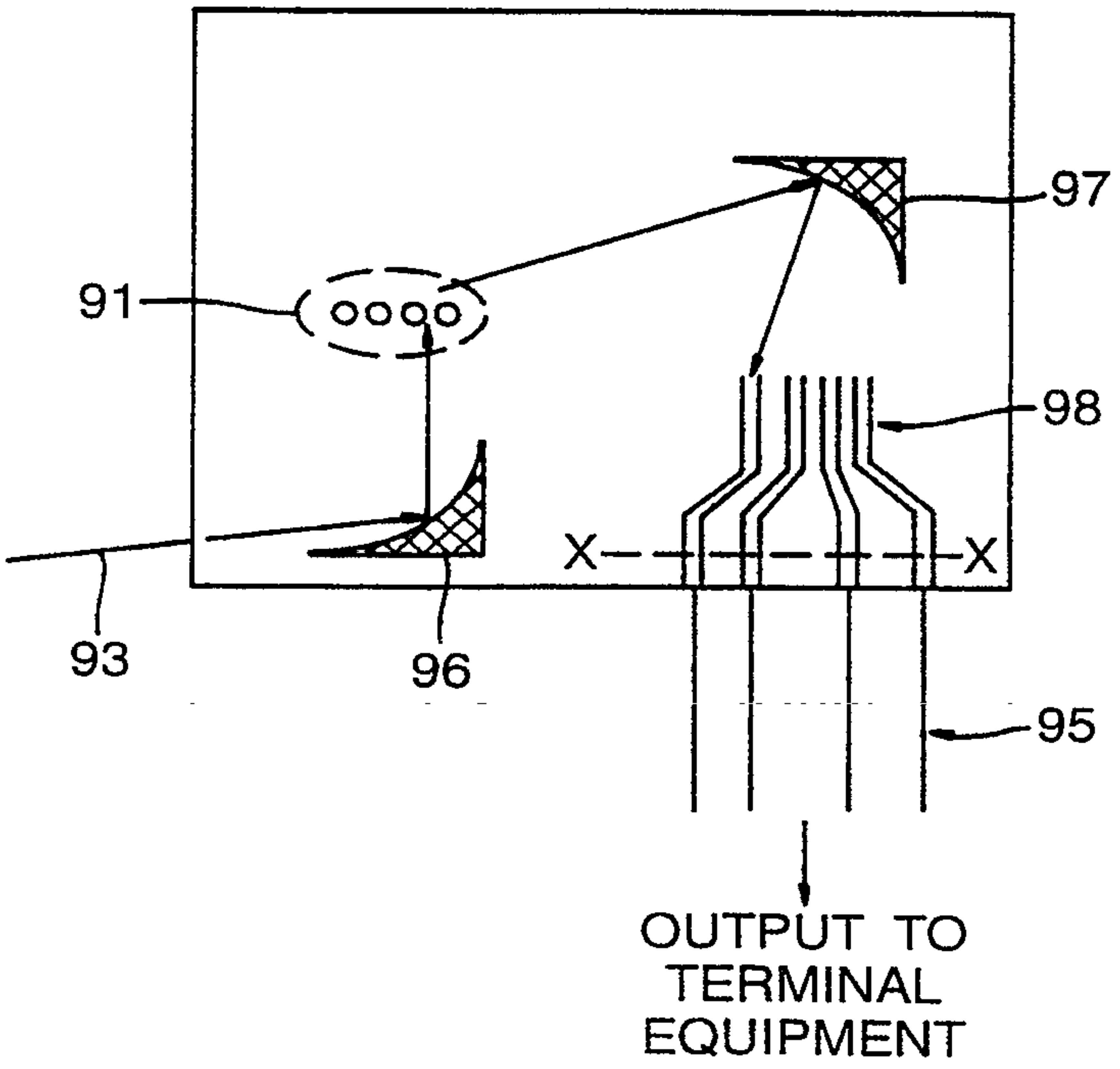


Fig.9b.

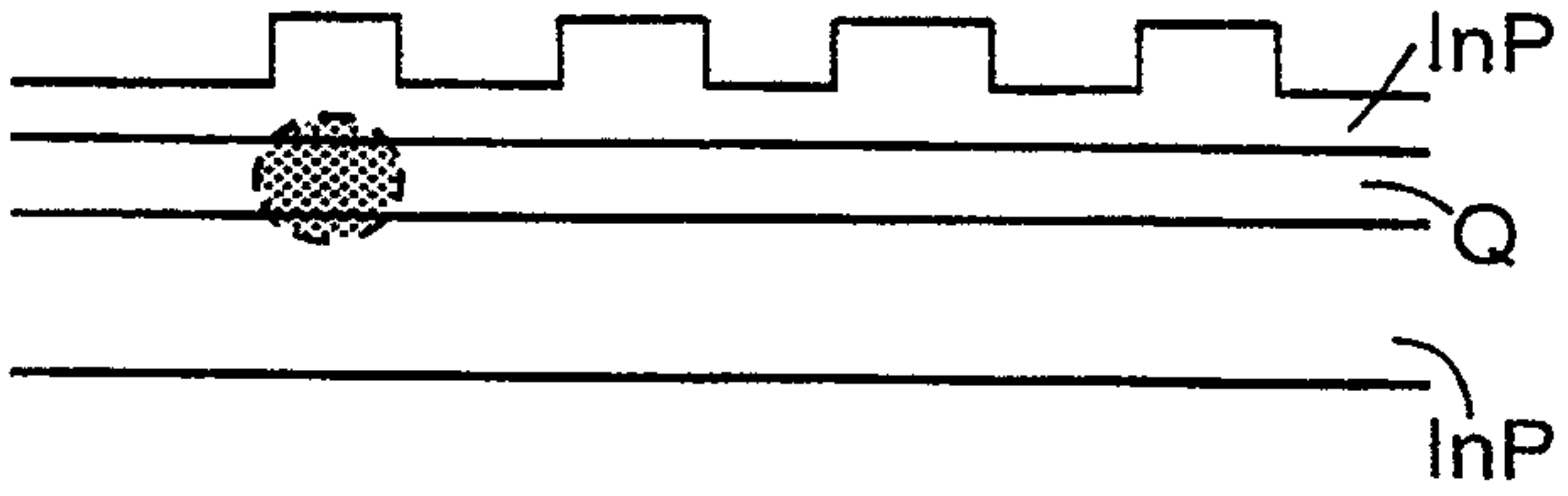


Fig.11.

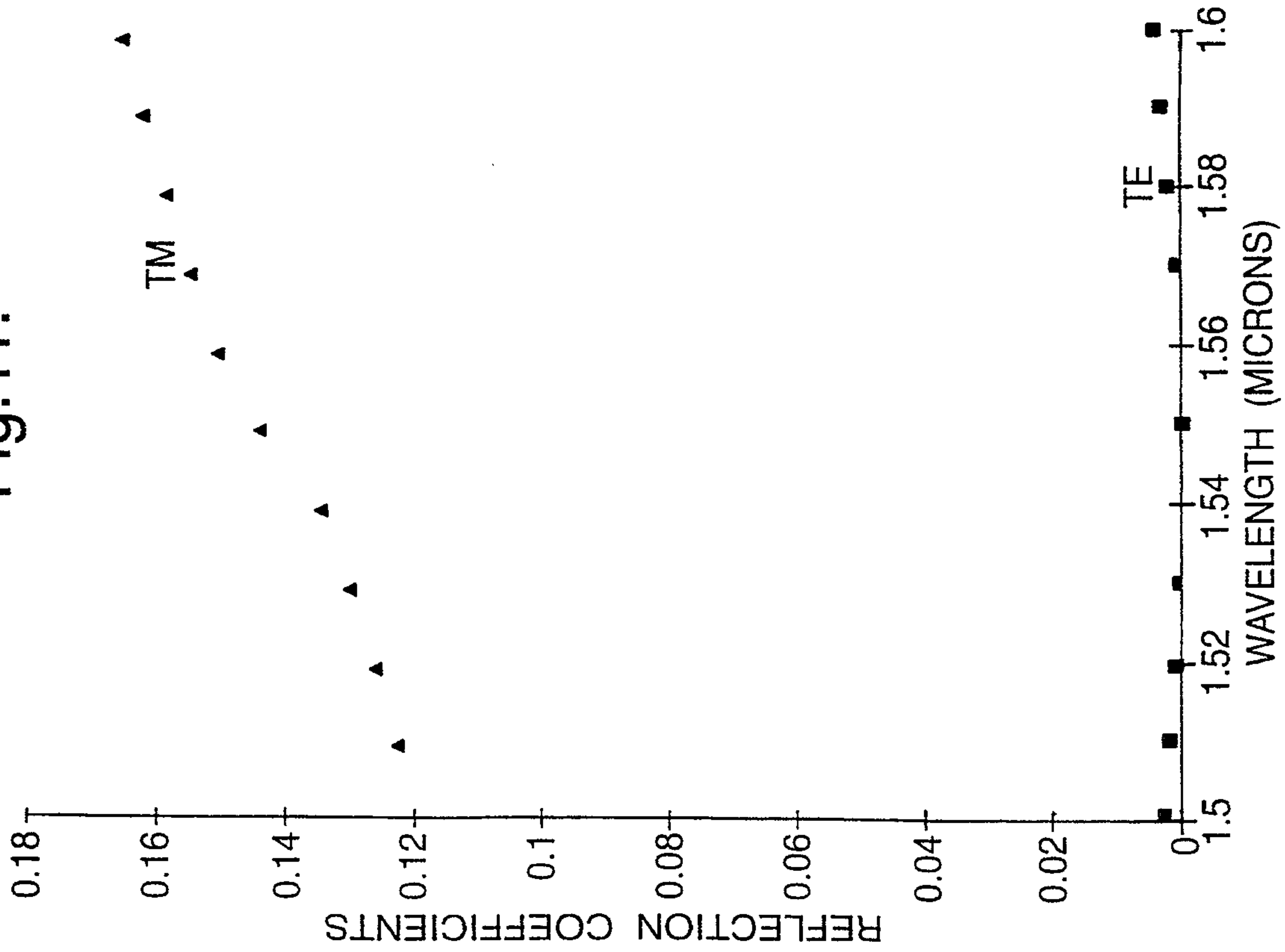
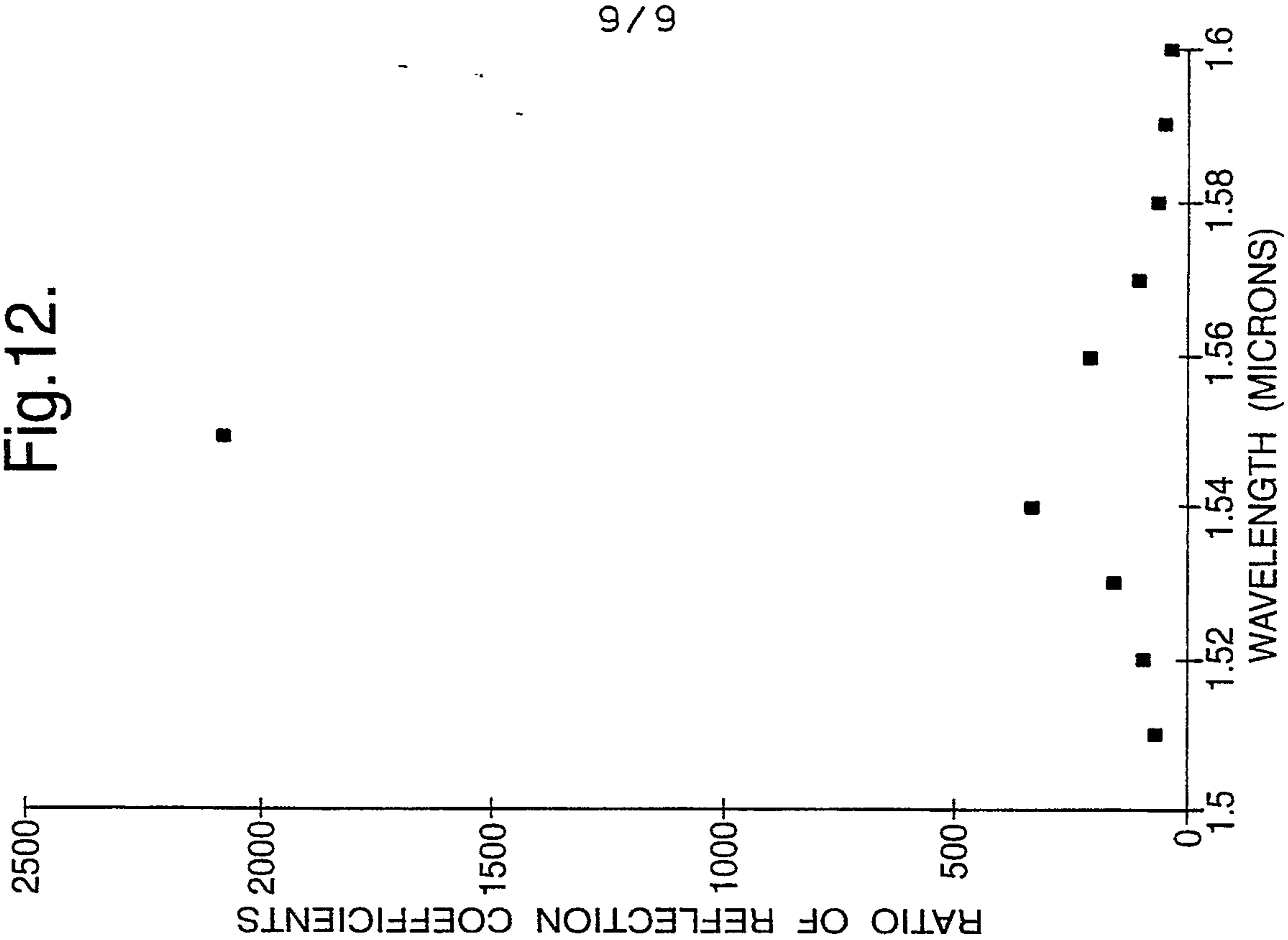
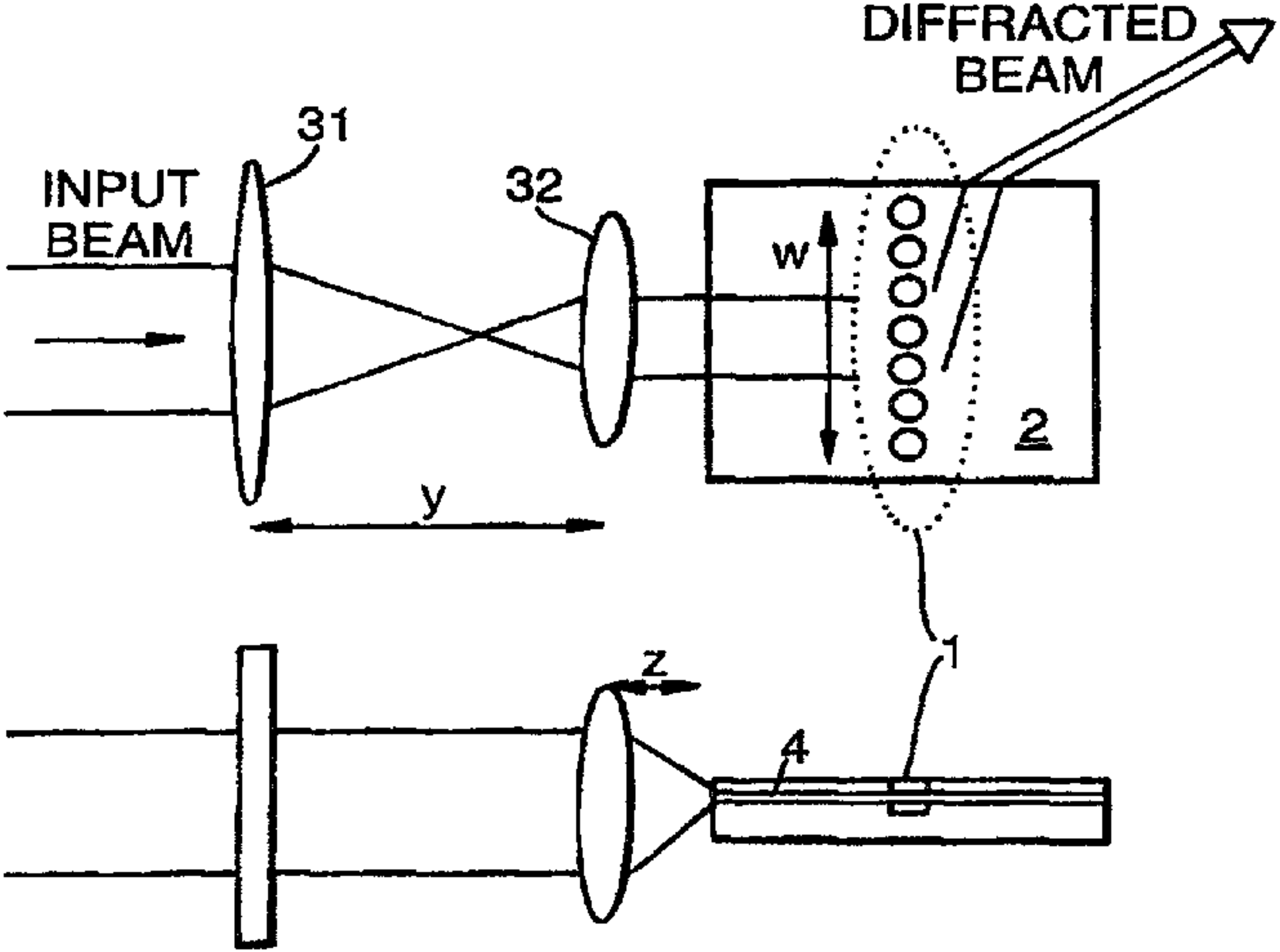

REFLECTION COEFFICIENTS
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1.5
1.52
1.54
1.56
1.58
1.6
WAVELENGTH (MICRONS)
TM
TE

Fig.12.


RATIO OF REFLECTION COEFFICIENTS
2500
2000
1500
1000
500
0
1.5
1.52
1.54
1.56
1.58
1.6
WAVELENGTH (MICRONS)


DIFFRACTED BEAM
31
INPUT BEAM
32
w
2
y
1
z
4