(54) Title: OPTICAL FIBRE COUPLER
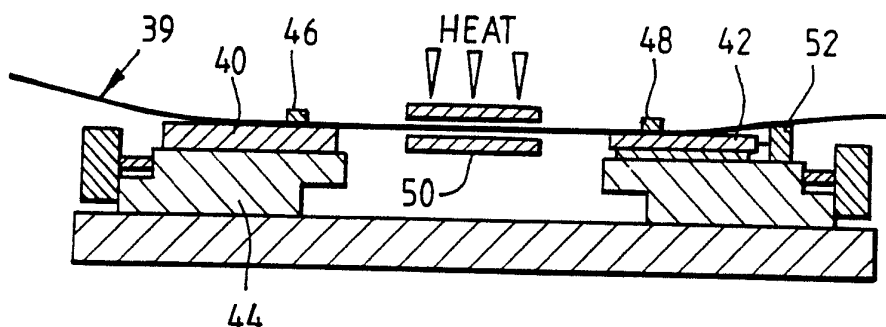
(57) Abstract

A method of forming a multiport optical fibre coupler in which a bundle of seven optical fibres are located in close-packed hexagonal array within a capillary tube and twisted. An optical source is coupled to an outer fibre. A fused, tapered coupler is formed, the tapering being stopped when the minimum of optical power outputs is first maximised. This provides a 6x7 optical fibre coupler. Also disclosed is a 7x7 optical fibre coupler formed by fusing the coupler during formation sufficiently to provide that the maximum insertion loss through the device between any input and output is minimised.

## OPTICAL FIBRE COUPLER

This invention relates to optical fibre couplers.

With the advent of high capacity optical networks the need for low loss coupling arrays is becoming increasingly important. Both 1xN and MxN devices are of interest, depending on the network architecture, which can be made arbitrarily large by concatenating elementary 1x2 or 2x2 couplers. Couplers such as these can be fabricated in a number of different ways, for example using planar technology or by using fused fibre techniques. Both of these approaches have their restrictions. Planar devices although very small in size can suffer from reflections and relatively high losses when pigtailed onto standard system fibres. Fused fibre devices can be fabricated directly from system fibre, thus overcoming the problem of reflections and coupling losses, but concatenating these devices to form large arrays requires considerable space which is at a premium in modern telecommunications networks.

The use of fused fibre technology has been made more attractive recently in modern telecommunications networks by the development of monolithic devices with many input/output ports, such as 3x3, 4x4 and 1x7 couplers. See for example: Mortimore, D. B.; "Monolithic 4x4 single-mode fused coupler", Electronics Letters 25, 10, pp 682-683, 1989 and Mortimore, D. B. and Arkwright, J. W.; "Monolithic wavelength flattened 1x7 single-mode fused coupler", Electronics Letters 25, 9, pp 606-607, 1989. These devices allow a considerable saving in space over arrays formed from elementary couplers having fewer ports.

According to a first aspect of the present invention a method of forming an optical fibre coupler includes the steps of: forming a fibre bundle of seven optical fibres in

- 2 -

a close-packed hexagonal array having a central fibre and six outer fibres;

coupling an optical source to one of the outer fibres to provide an optical power output at each of the seven
5   fibres; and

forming a fused, tapered coupler from the fibre bundle, the tapering being stopped when the minimum of the optical power outputs from the seven fibres is first maximised.

10   The applicants have found that such a fibre bundle when so formed into a tapered optical star coupler provides a coupler in which the linear spread of insertion losses between an input outer fibre and the seven fibres is near the minimum for the device and so provides a usefully low
15   insertion loss, 6x7 star coupler having the characteristics of normal fused fibre devices, i.e. low splice loss, ease of manufacture, good temperature stability, and ruggedness.

Preferably the fibre bundle threaded within a capillary tube and is twisted prior to forming the fused,
20   tapered coupler: the twisting tends to increase the consistency of the coupler formation.

The minimum of the optical powers output from the fibres is preferably determined by monitoring the power output from each of the seven fibres. However, if the
25   fibre formation techniques and apparatus employed to form the coupler can be made sufficiently repeatable, monitoring of fewer output powers may provide sufficient information to determine when tapering should stop. For example, it may be found that only one of any fibres symmetrically disposed
30   relative to the outer fibre coupled to the optical source need be monitored to determine when the minimum of the output powers has been maximised.

In general, a coupler formed by the method according to the present invention will not also be a satisfactory
35   1x7 coupler.

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That is, there will not be an equal split of optical power
from an optical source coupled to the centre fibre to the
seven fibres of the coupler. Consequently, it will not, in
general, be a satisfactory 7x7 star coupler. For such an
5    array of seven fibres the point of equal coupling from the
central fibre to the seven fibres occurs before the
tapering has obtained a 6x7 coupler, for example.

As will be described in detail later, the degree of
fusion affects the coupling characteristics of a coupler
10    according to the present invention. The degree of tapering
needed to form a 1x7 coupler can be increased by increasing
the degree of fusion. This moves the degree of tapering
needed to obtain a 1x7 coupler towards the degree of
tapering needed to obtain a satisfactory 6x7 coupler
15    although the spread of insertion losses of the 6x7 coupler
may be worse than for zero fusion.

Accordingly, coupler according to the first aspect is,
a sufficiently fused to provide that the maximum insertion
loss through the device between any input and any output
20    fibre is minimised.

The preferred way to control the degree of fusion is
by controlling the temperature of the fusion to obtain a
predetermined tension profile exerted on the fibres during
formation of the fused tapered coupler.

25    Methods of forming optical couplers according to the
present invention and the theory of operation of such
couplers will now be described, by way of example only,
with reference to the accompanying drawings in which:

Figure 1 is a diagram of an hexagonal close packed
30    array of seven fibres which serves as a model for a
theoretical analysis of a coupler according to the present
invention;

Figure 2 is a graph of the theoretical powers
propagating through a seven fibre array for the case of
35    off-axis fibre illumination;

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- 4 -

Figure 3 is a diagramatic cross-section of a fibre bundle prior to formation of a coupler according to the present invention;

Figure 4 is a schematic drawing of the distortion of the outer fibres due to the interaction with a surrounding capillary during formation of a coupler according to the method of the present invention;

Figures 5 and 6 are graphs of the theoretical powers propagating through a seven fibre array for the case of off-axis illumination for two different degrees of fusion;

Figure 7 is a graph of the theoretical powers propagating through a seven fibre array for the case of central fibre illumination;

Figures 8a and 8b are graphs of the theoretical wavelength responses for a device optimised at 1300nm for central fibre illumination and off-axis illumination, respectively;

Figures 9a and 9b are graphs of the theoretical wavelength responses for a device optimised at 1530nm for central fibre illumination, and off-axis illumination respectively;

Figures 10a and 10b are graphs of the wavelength response of a device fabricated to operate at 1300nm for central fibre illumination and off-axis illumination, respectively; and

Figure 11 is a schematic diagram of the fusion apparatus suitable for forming a coupler according to the present invention.

The mode coupling between an arbitrary array of N parallel, weakly-coupled optical fibres can be described by a set of well-known coupled differential equations: Snyder, A.W.; and Love, J.D.; "Optical Waveguide Theory" (Chapman and Hall, 1983) pp 542).

$$\frac{da_n}{dz} + i\beta_n a_n = -i\sum_{\substack{n=1 \\ n \neq m}}^{N} C_{mn} a_m \qquad (1)$$

SUBSTITUTE SHEET

- 5 -

where $a_n$ is the z dependent modal amplitude in fibre n, $\hat{}_n$ is the propagation constant of the mode in fibre n, and $C_{mn}$ is the coupling coefficient between fibres m and n.

By making the substitution:

$$a_q = A_q e^{-i\beta z} \qquad (2)$$

the fast oscillation of the electromagnetic field can be removed. A further substitution of:

$$A_q = B_q e^{-i\lambda z} \qquad (3)$$

removes the z-dependence giving a set of coupled equations in $B_n$ of the form:

$$(\beta_n - \beta - \lambda) B_n = \sum_{m=1}^{N} C_{mn} B_m \qquad (4)$$

In order to find non-trivial solutions to these equations the derived characteristic equation is solved giving the Eigenvalues $\lambda$ and hence the vectors $B_n$.

Once the Eigenvalues and vectors have been found, the modal field, $A_n$, propagating through the array can be calculated from a linear combination of the Eigenvectors:

$$\begin{pmatrix} A_1 (z) \\ \cdot \\ \cdot \\ \cdot \\ A_N (z) \end{pmatrix} = k_1 e^{-i\lambda_1 z} \begin{pmatrix} B_1 \\ \cdot \\ \cdot \\ \cdot \\ B_N \end{pmatrix}_1 + \dots k_N e^{-i\lambda_N z} \begin{pmatrix} B_1 \\ \cdot \\ \cdot \\ \cdot \\ B_N \end{pmatrix}_N \qquad (5)$$

where the constants k are given by the input conditions to the array.

The powers propagating in each fibre in the array can then be found from the relation;

$$P_n(z) = |A_n(z)|^2 \qquad (6)$$

SUBSTITUTE SHEET

- 6 -

Referring to Figure 1, a fibre $f_0$ is surrounded by fibres $f_1$ to $f_6$ in an hexagonal close packed array of fibres where the propagation constants of the fibres in the outer ring, $\beta_r$, may differ from that of the central fibre, $\beta_0$. By considering nearest neighbour coupling only, and assuming that the coefficients describing the coupling between the central and each outer fibre and between adjacent fibres in the outer ring are equal, equations (1) for such an array can be simplified. By considering specific input conditions the equations can be simplified further. For the purposes of this analysis the characteristics of the fibre array can be defined completely by considering just two input conditions: that of unit illumination of the central fibre $f_0$ and that of unit illumination of a single off-axis fibre eg. fibre $f_1$.

For illumination of the central fibre $f_0$ all the outer fibres (generally denoted $f_r$, where r = 1 to 6) have identical coupling characteristics and equations (1) reduce to:

$$\frac{da_r}{dz} + i\beta_r a_r = -i(2Ca_r + Ca_0)$$

$$\frac{da_o}{dz} + i\beta_o a_o = -i6Ca_r \tag{7}$$

where the subscript r refers to the fibre in the outer ring of the structure and C is the characteristic coupling constant.

Substituting (2) and (3) into (7) gives two coupled equations in $B_0$ and $B_r$ giving a characteristic equation of the form:

$$\begin{vmatrix} \beta_o - \beta - \lambda & 6C \\ C & \beta_r - \beta + 2C - \lambda \end{vmatrix} = 0 \tag{8}$$

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Solving the developed quadratic gives the two Eigenvalues:

$$\lambda_{\pm} = C \pm K \tag{9}$$

where

$$K = C \sqrt{6 + \left(1 + \frac{\beta_r - \beta_o}{2C}\right)^2} \tag{10}$$

and the corresponding Eigenvectors can be written:

$$\begin{pmatrix} B_o \\ B_r \end{pmatrix}_{\pm} = \begin{pmatrix} \dfrac{-6C}{\dfrac{\beta_o - \beta_r}{2} - C \pm K} \\ 1 \end{pmatrix} \tag{11}$$

From equation (5) the field propagating in the z direction through the fibre array is given by:

$$\begin{pmatrix} A_o(z) \\ A_r(z) \end{pmatrix} = k_1 e^{-i\lambda_+ z} \begin{pmatrix} B_o \\ B_r \end{pmatrix}_{+} + k_2 e^{i\lambda_- z} \begin{pmatrix} B_o \\ B_r \end{pmatrix}_{-} \tag{12}$$

and from equation (6) the powers in the central and outer fibres are given by:

$$P_r(z) = \frac{C_o^2}{K^2} \sin(Kz)^2 \tag{13}$$

$$P_o(z) = 1 - 6P_r(z)$$

For off-axis illumination equations (7) can be simplified due to the symmetry of the array by setting $a_2 = a_6$ and $a_3 = a_5$, where the subscripts refer to the correspondingly referenced fibre $f_i$ of the array shown in Figure 1. Following the same steps as detailed above leads to a characteristic equation of the form:

$$\begin{vmatrix} (\beta_r-\beta-1) & 2C_r & 0 & 0 & C_o \\ C_r & (\beta_r-\beta-1) & C_r & 0 & C_o \\ 0 & C_r & (\beta_r-\beta-1) & C_r & C_o \\ 0 & 0 & 2C_r & (\beta_r-\beta-1) & C_o \\ C_o & 2C_o & 2C_o & C & (\beta_o-\beta-1) \end{vmatrix} = 0$$

(14)

from which the Eigenvalues and vectors, the modal amplitudes, and the powers propagating in each fibre can be calculated.

Now consider the case where the propagation constants of the central and outer fibres are equal, e.g. an array of identical fibres. The powers propagating through the array for off-axis illumination of fibre $f_1$ are shown in Figure 2. The powers are plotted against K.z in order to remove the dependence of the interaction length on the coupling coefficient C. $P_0$ is the power propagating through the central fibre and $P_1$, $P_2$, $P_3$ and $P_4$ are the powers propagating through the outer fibres and in which $P_5=P_3$, $P_6=P_2$.

The method of forming a coupler according to the first aspect of the present invention comprises pulling the coupler until the minimum of the optical powers in the seven output fibres is first maximised for the particular degree of fusion that pertains during formation. This amount of fusion is to some degree arbitrary although the particular degree of fusion will affect the actual insertion losses obtained after tapering. For off-axis illumination of such a 6x7 coupler a theoretical minimum spread of 5.9% occurs for $\gamma=0$ and K.z =2.2 for this coupler.

It has been shown that an extension in the effective interaction length can be achieved for devices consisting of seven fibres inserted into a capillary tube of glass which has a slightly depressed index with respect of that

of pure silica by varying the degree of fusion of the structure. (Mortimore, D. B. and Arkwright, J. W. "Performance tuning of wavelength-flattened 1x7 fused couplers", OFC 1990.)

5          As the structure fuses together during the fabrication process the effect of the capillary tube is twofold. Firstly, the proximity of the tube causes a slight increase in the propagation constants of the outer fibres and, secondly, the interaction of the capillary tube with the

10       array causes the outer fibres to be distorted out of round. This is illustrated in Figure 4 in which an outer fibre 24 has had its cross-section flattened at sections 26, 28 and 30 due to its interaction with adjacent fibres (not shown) and the portion adjacent the capillary distorted. This

15       tends to decrease the propagation constants of the outer fibres. The combined effects enable a mismatch to be created between the propagation constants of the central and outer fibres dependent on the degree of fusion of the structure achieved during fabrication. As the propagation

20       constants of the outer fibres vary relative to that of the central fibre so the maximum power coupled out of the central fibre changes. In order to quantify the degree of fusion of the structure, the dimensionless parameter $\gamma = B_0 - B_r/2C$ is introduced, where $\gamma = 0$ corresponds to the case

25       of equal propagation constants, and $\gamma = 1$ corresponds to the degree of fusion needed to give total power transfer between the central and outer fibres for the case of central fibre illumination.

          Varying the degree of fusion of the device also

30       affects the distribution of the coupled powers for off-axis illumination. Figure 2, already referred to, shows the calculated coupled powers from the above model as a function of K.z for $\gamma = 0$. Figures 5 and 6 show the calculated coupled powers for $\delta = 0.44$ and 1 respectively.

35       Referring now to Figure 7 there is plotted $P_0$, the power propagating through the central fibre $f_0$, and $P_r$, the

- 10 -

power propagating through a single outer fibre for central
fibre illumination of the fibre array of Figure 1.  The
solid line corresponds to $\gamma=0$, and the dashed line
corresponds to $\gamma=1$.  Point A shows the effective extension
5    in the interaction length for a value of $\gamma=1$.

Thus for $\delta>0$ equal coupling can occur at two distinct
points every cycle.  By choosing to operate at the second
equal coupling point the effective interaction length for
a 1x7 device can be extended towards point A on the dashed
10   curve of Figure 7.

It can be seen from a comparison of Figures 2 and 7
that the interaction length needed to produce the lowest
maximum insertion loss to the outer fibres for off-axis
illumination is, in this case, greater than that required
15   for equal coupling between the central fibre and outer
fibres if $\gamma=0$.  In order to produce a device in which the
full 7x7 configuration can be satisfactorily utilised, it
is necessary to extend the interaction length needed to
give equal coupling to the outer fibres for central fibre
20   illumination towards the length at which the 6x7 coupler is
optimised by increasing the degree of fusion during
formation of the coupler away from the zero fusion needed
to give the optimum split for off-axis illumination.  For
the above device $\gamma=0.44$ gives a lower 'worst case'
25   insertion loss for the 7x7 device.  At this degree of
fusion the powers carried on each fibre at the point of
smallest insertion loss are:

$P_1=21.0\%;$

$P_2=P_4=P_6=13.0\%;$

30   $P_3=P_5=13.4\%;$   and

$P_0=13.2\%.$

This is shown in Figure 5.

The worst case insertion loss through the device for
off-axis illumination is therefore given by the power on
35   fibres $f_2$, $f_4$ and $f_6$ having a value of 8.86 dB.  Due to the
reciprocal nature of the device, it can be seen that

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- 11 -

illuminating the central fibre under the same conditions
will result in a near identical result in which all the
outer fibres carry 13.2% and the central input fibre
carries the remaining 21.0% of the power. Thus an overall
5   optimum result for all input conditions is achieved at this
value of γ, where by optimum is meant the lowest maximum
insertion loss.

The optimum degree of fusion to produce the optimum
7x7 coupler can be determined by trial and error for the
10  particular materials and device fabrication chosen. Once
determined couplers are formed stopping at the point when
the maximum of the insertion losses reaches a minimum.
However, the invention in its broadest aspect provides a
coupler optimised as a 6x7 coupler for the degree of fusion
15  pertaining during its formation.

By assuming a linear dependence of the coupling
coefficient with respect to wavelength, the theoretical
wavelength response of the device can be found from
equations (6). By holding the interaction length constant
20  and varying the coupling coefficient, the response of the
device over the range 1200nm - 1600nm is found. Figures 8a
and 8b show the theoretical wavelength response for a 7x7
coupler optimised at 1300nm for central and off-axis
illumination, respectively. Figures 9a and 9b show the
25  theoretical wavelength response for a device optimised at
1530nm for central fibre illumination and off-axis
illumination.

Referring now to Figure 3, there is illustrated an
exemplary arrangement for holding the fibres $f_0$ to $f_6$ during
30  formation of a coupler according to the present invention
in which seven standard, single mode, 124.7μm outside
diameter fibres 20, 21 have been stripped of their primary
coating, cleaned and constrained in a hexagonal,
close-packed array by insertion into a tight fitting silica
35  base glass capillary tube 22 having a refractive index
slightly less than pure silica. The central fibre is

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referenced as 21.    The particular capillary used was formed
from a tube of 'Vycor' glass obtainable from Corning Glass
pulled down to have a nominal inside diameter of 380-384μm.
A tube of the same refractive index as the fibre cladding
is also expected to work successfully.    The 'Vycor' tube
material was chosen because its refractive index is lower
than that of the silica fibre cladding so that leakage of
the optical field into the tube material is minimised.
Capillaries of other suitable material may be used.    Other
dimensions of fibre and tube may be used but the elipticity
should preferably be less than or equal to about 1.0%.

        A standard fused coupler fabrication equipment as
shown in Figure 11 was used to form the tapered coupler the
fibre bundle being heated and pulled in the usual manner.

        Couplers were made as follows:    Seven lengths of
standard,  index-matched cladding fibre of about 1 metre
each had about 20cms of cladding removed from one end.
These were then threaded into the 30mm long Vycor capillary
tube 22.    It has been found important to carry this out in
very clean conditions,  in a clean environment and  with
repeated wiping of the fibres with a cloth impregnated with
a solvent,  for example ethanol.

        The fibres 20 and 21 were identified by shining light
down each fibre in turn and from visual inspection of the
fibres with a lens.    Each fibre tail was then tagged
according to its position in the array.    The fibre tails
were then spliced to normal clad fibres about 36mm from the
capillary,  which distance depends  on  the particular
apparatus being used.

        The fibre bundle 39 and capillary were then taped to
mounts 40 and 42, the former on a motorised slide 44 of the
tension fusion apparatus,  about 75mm apart  by means  of
fibre holding clamps 46 and 48.    One slide mount was
rotated to twist the bundle of fibres.    About 1 revolution
is needed for each 25mm between the slide mounts.    The

- 13 -

applicant has found that this twist greatly improves the
consistency of the coupler formation.

The coupler was then formed by heating the capillary
tube whilst pulling the fibre bundles apart in a ceramic
5    crucible 50. A semi-conductor laser operating at 1300nm was
spliced onto an outer fibre of the device, and all the
outputs were monitored individually during the pulling
process.  The pulling process was stopped when the maximum
of all the output insertion losses first reached a minimum
10   and the device potted.

The rate of elongation of the coupler during fusion is
set at in the region of 200μm per second which is slow
enough to monitor progress of the coupler formation.  The
tuning is controlled via the tension applied during pulling
15   of the coupler with feedback from a tension sensor 52 to
the heater of the fusion apparatus heating zone to maintain
the temperature for the desired tension. The higher the
tension the lower the temperature hence less fusion of
fibres than if a lower tension were preset.

20   A well-fused coupler, as described in this application
has a tension of 1gm reducing linearly to 0.3gm over 10mm
of elongation and maintained until the stopping point is
reached.  A lightly fused coupler a tension of 3gm reducing
linearly to 2gm which is maintained until the stopping
25   point is reached.  These tensions result in fusion
temperatures near the softening temperature of the fibres,
in this case about 1600°C.

These values will need to be varied for fibres of
different dimensions.  They will also vary with the
30   crucible size etc. of the particular fusion apparatus used
but will be readily determined by trial and error.  The
device is then ready for packaging.

Other capillary tubes may be suitable for the
manufacture of couplers according to the present invention
35   - for example a silica tube lined with a lower index
coating pulled down to a capillary of the desired internal

- 14 -

diameter or ordinary silica if pulled to have the same or slightly lower refractive index as the cladding of the fibres.

The insertion losses from each input to every output
5   were measured and the wavelength response of the device was measured from both the central and one outer input to all outputs.

The measured insertion losses at 1300nm of every possible path through the device are given in table 1,
10   these values of insertion loss include one fusion splice, which adds a loss of = <0.1dB to the measured values. The mean value of the insertion loss is 8.62 dB with a standard deviation of 0.52 dB, the worst case insertion loss is 9.63 dB. The mean value of the excess loss at 1300nm, from each
15   input fibre is 0.14 dB with a standard deviation of 0.06 dB. The spread in the power coupled to the output fibres as a percentage of the transmitted power has a minimum value of 4.3 per cent for the case of central fibre illumination, and 4.5 per cent for the best off-axis
20   illumination. This spread in powers for the off-axis illumination agrees well with the theoretical minimum value of 5.9 per cent, and is better than the expected minimum of 8 per cent predicted for the complete 7x7 device. This suggests the assumption of weak coupling breaks down for
25   higher degrees of fusion.

The wavelength response taken from the central input fibre shows a similar response to all of the outer output fibres, as would be expected from symmetry, and a hightened response to the power remaining on the central fibre. The
30   equal coupling point is centred near 1300nm, Figure 10a. The wavelength response from a single off-axis input fibre is again centred near 1300nm and shows a low wavelength sensitivity on all fibres, giving an acceptable operating region of about 120nm, for which insertion losses of =<10
35   dB are achieved, Figure 10b. The responses gained experimentally are seen to agree well with those calculated

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from equations 6.  Figure 8a shows the fraction of optical power remaining in the fibre $P_1$ and the remaining fibres ($P_i$, $i \neq 1$) for off-axis launch at 1300nm.  Figure 8b shows the fraction of optical power remaining in the central fibre ($P_1$) and the fraction coupled to the outer fibres ($P_r$) for on-axis launch at 1300nm.  Figures 9a and 9b show the responses for the same launch conditions as Figures 8a and 8b, respectively, but at 1520nm.

The device described has been fabricated to give optimum results at 1300nm, however it can be seen from Figures 10a and 10b, that the wavelength response for central fibre illumination is distinctly asymmetric about the operating wavelength.  The trend illustrated in Figures 10a and 10b which show that for decreasing wavelength the powers coupled to the central and outer fibres converge, whereas for longer wavelengths the power on the central fibre starts to diverge sharply from that carried on the outer fibres.  By choosing to operate at a longer wavelength therefore, say 1550nm, the wavelength response for central fibre illumination has the useful property of being wavelength flattened at lower wavelengths.  A device such as this has a reduced wavelength response for central fibre illumination, over the window 1280nm - 1550nm, hence covering both the standard telecoms wavelengths.

In this specification, the term "optical" is intended to refer to that part of the electromagnetic spectrum which is generally known as the visible region together with those parts of the infrared and ultraviolet regions at each end of the visible region which are capable of being transmitted by dielectric optical waveguides such as optical fibres.

- 16 -

CLAIMS

1.    A method of forming an optical fibre coupler including the steps of:

        forming a fibre bundle of seven optical fibres in a close-packed hexagonal array having a central fibre and six outer fibres;

        coupling an optical source to one of the outer fibres to provide an optical power output at each of the seven fibres; and

        forming a fused, tapered coupler from the fibre bundle, the tapering being stopped when the minimum of the optical power outputs from the seven fibres is first maximised.

2.    A method as claimed in either of claims 1 and 2 in which a portion of the fibre bundle lies within a capillary tube.

3.    A method of forming an optical fibre coupler as claimed in claim 2 in which the coupler is fused sufficiently to provide that the maximum insertion loss through the device between any input and any output fibre is minimised.

4.    A method as claimed in any preceding claim in which the fibre bundle is twisted prior to forming the fused, tapered coupler.

5.    A method as claimed in any preceding claim in which degree of fusion is controlled by controlling the temperature of the fusion to obtain a predetermined tension profile exerted on the fibres during formation of the fused tapered coupler.

6.    A method as claimed in any preceding claim in which the optical power output by all seven fibres is monitored to determine when the minimum of the optical power outputs is first maximised.

7.    A method as claimed in any preceding claim in which the optical fibres are silica-based optical fibres.

- 17 -

8.    A method as claimed in claim 7 in which the optical source provides optical power at a wavelength greater than 1500nm.

9.    An optical fibre coupler comprising a fused tapered coupler having a centre fibre and six outer fibres, the taper being such that the minimum of optical powers split from an outer fibre to the seven fibres is at a maximum.

10.    An optical fibre coupler as claimed in claim 9 in which the insertion loss between the central fibre and any outer fibre is no greater than the maximum insertion loss from an outer fibre to any other fibre.

11.    A method of forming an optical fibre coupler as hereinbefore described.

12.    An optical coupler as hereinbefore described.
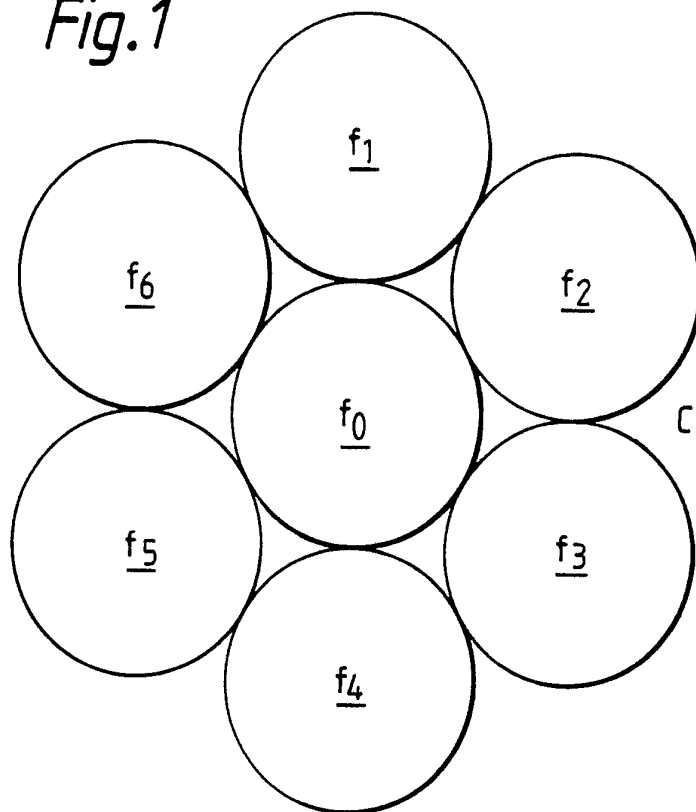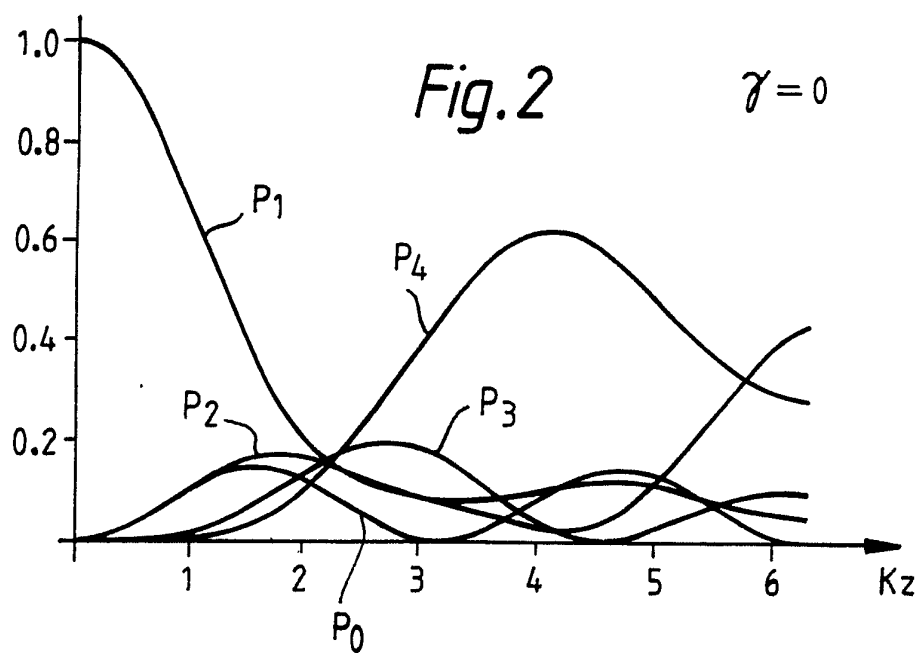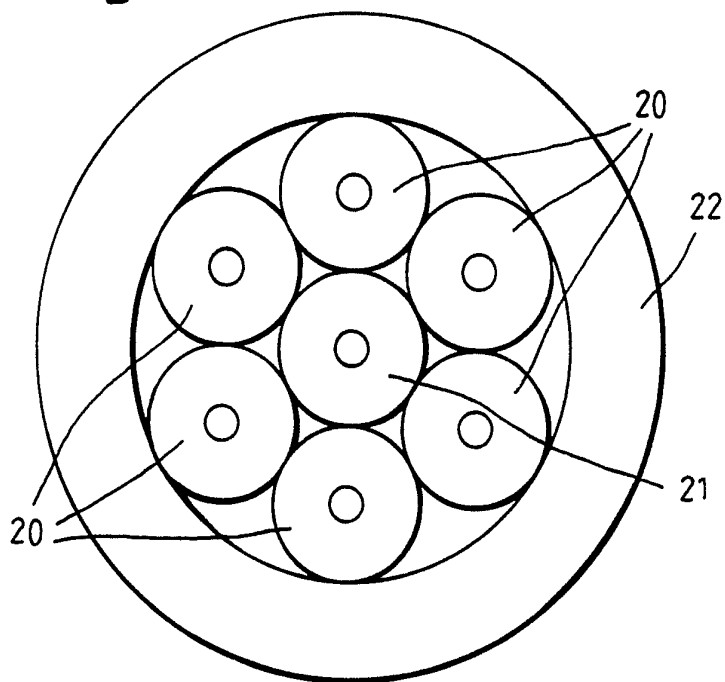
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## Fig.1



## Fig.2

$\gamma = 0$

2/7

## Fig.3



## Fig.4
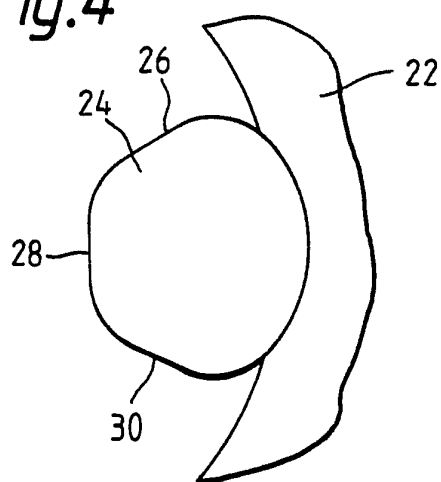
3/7
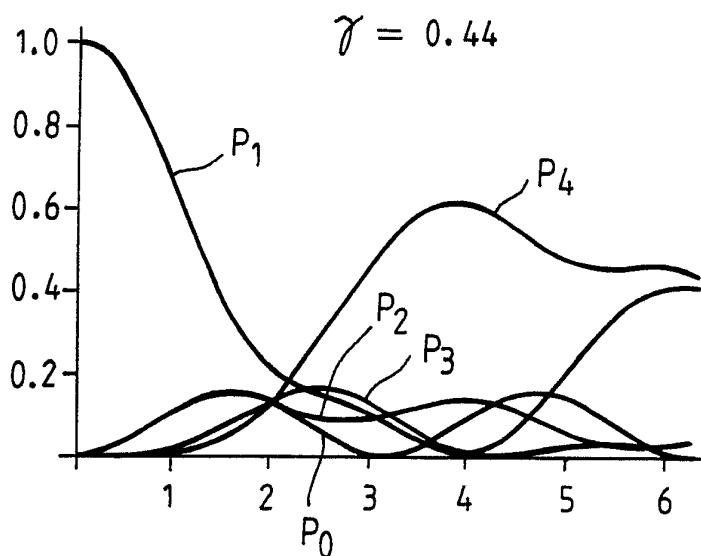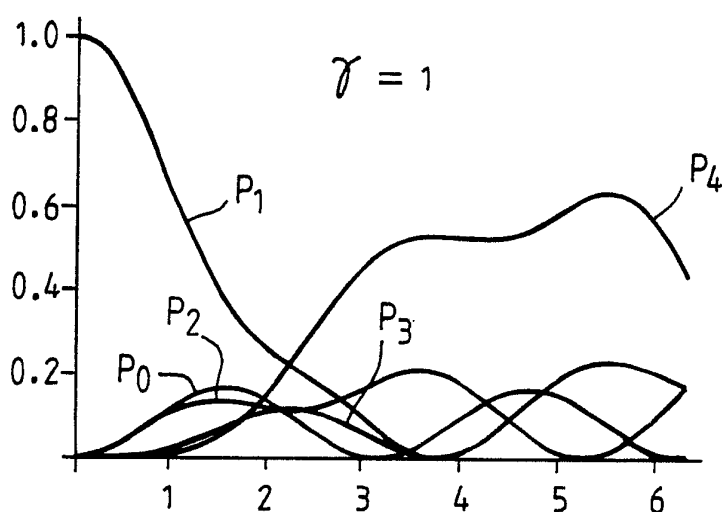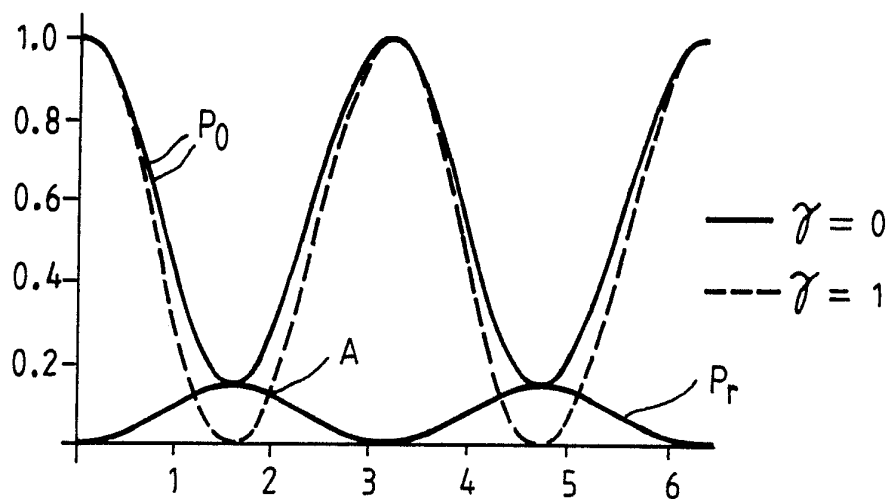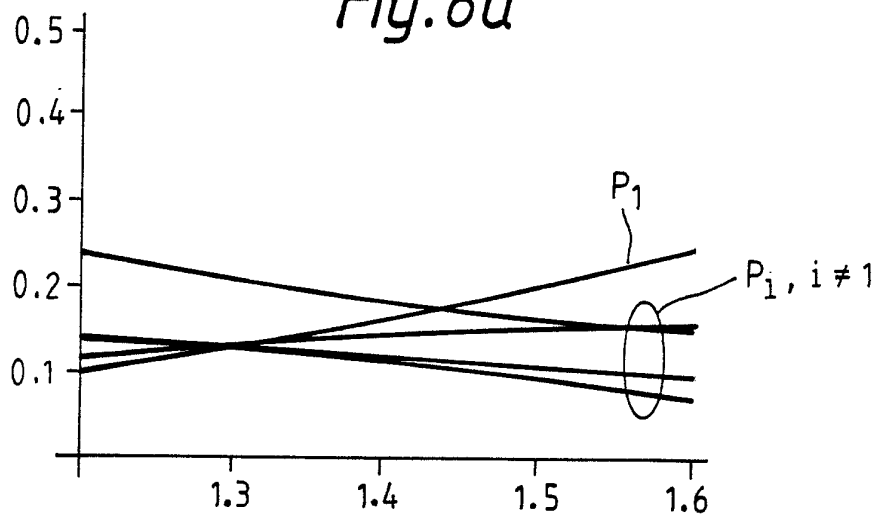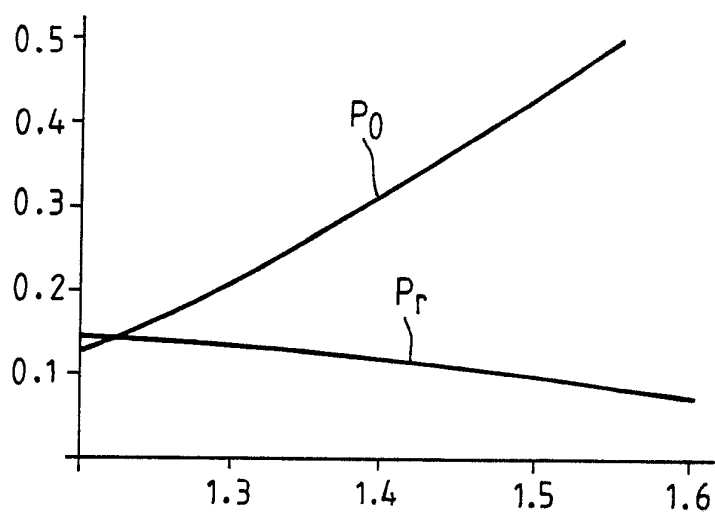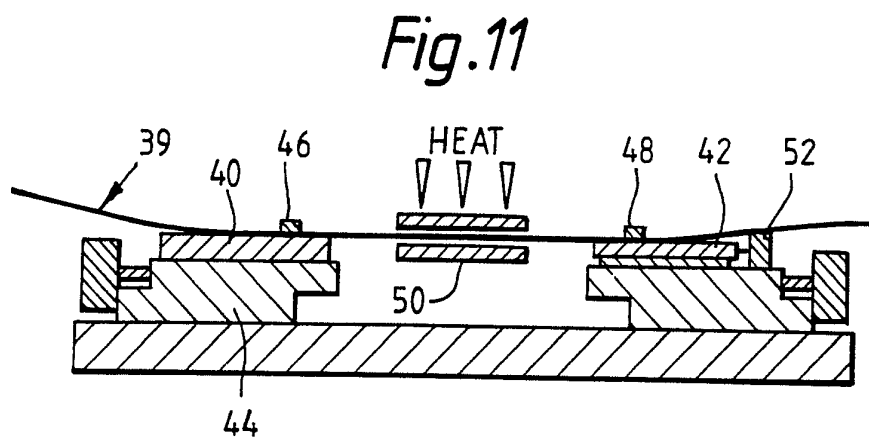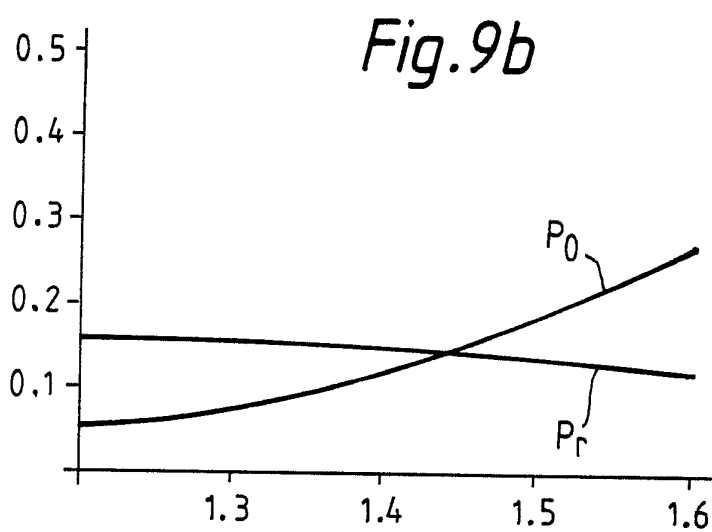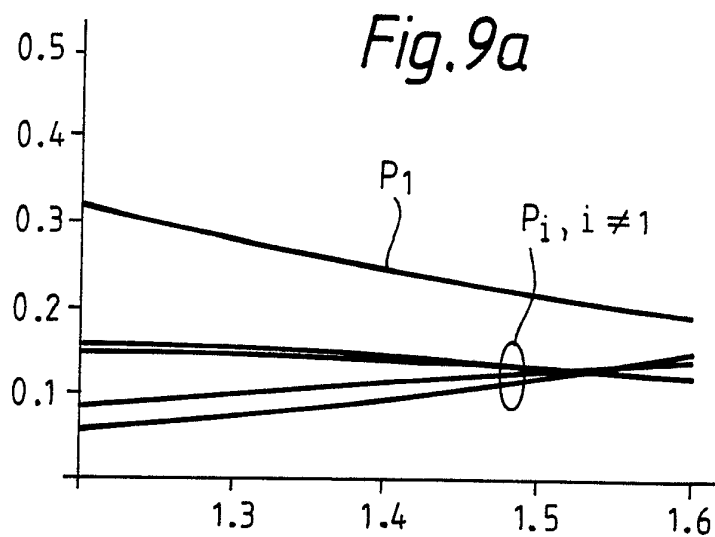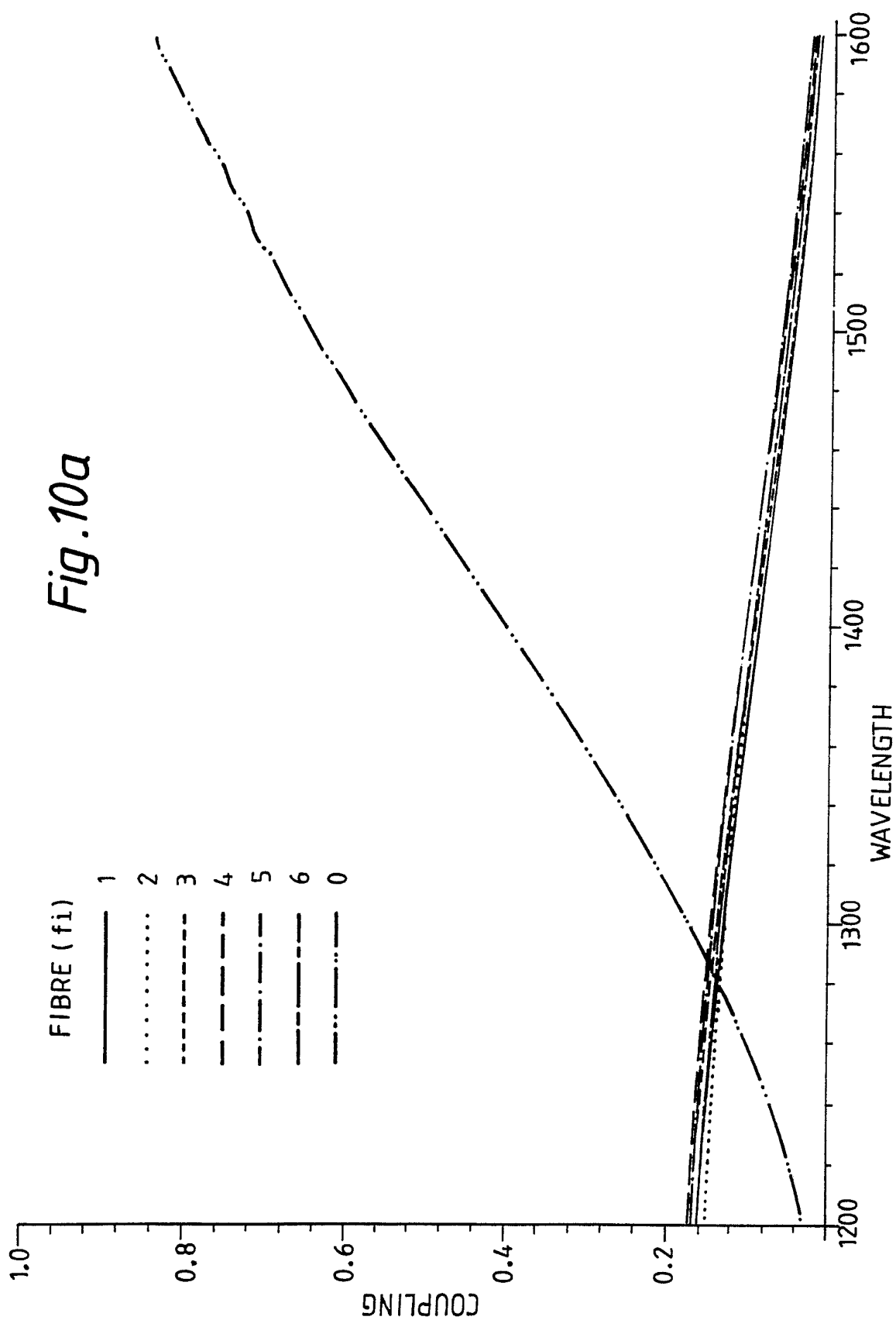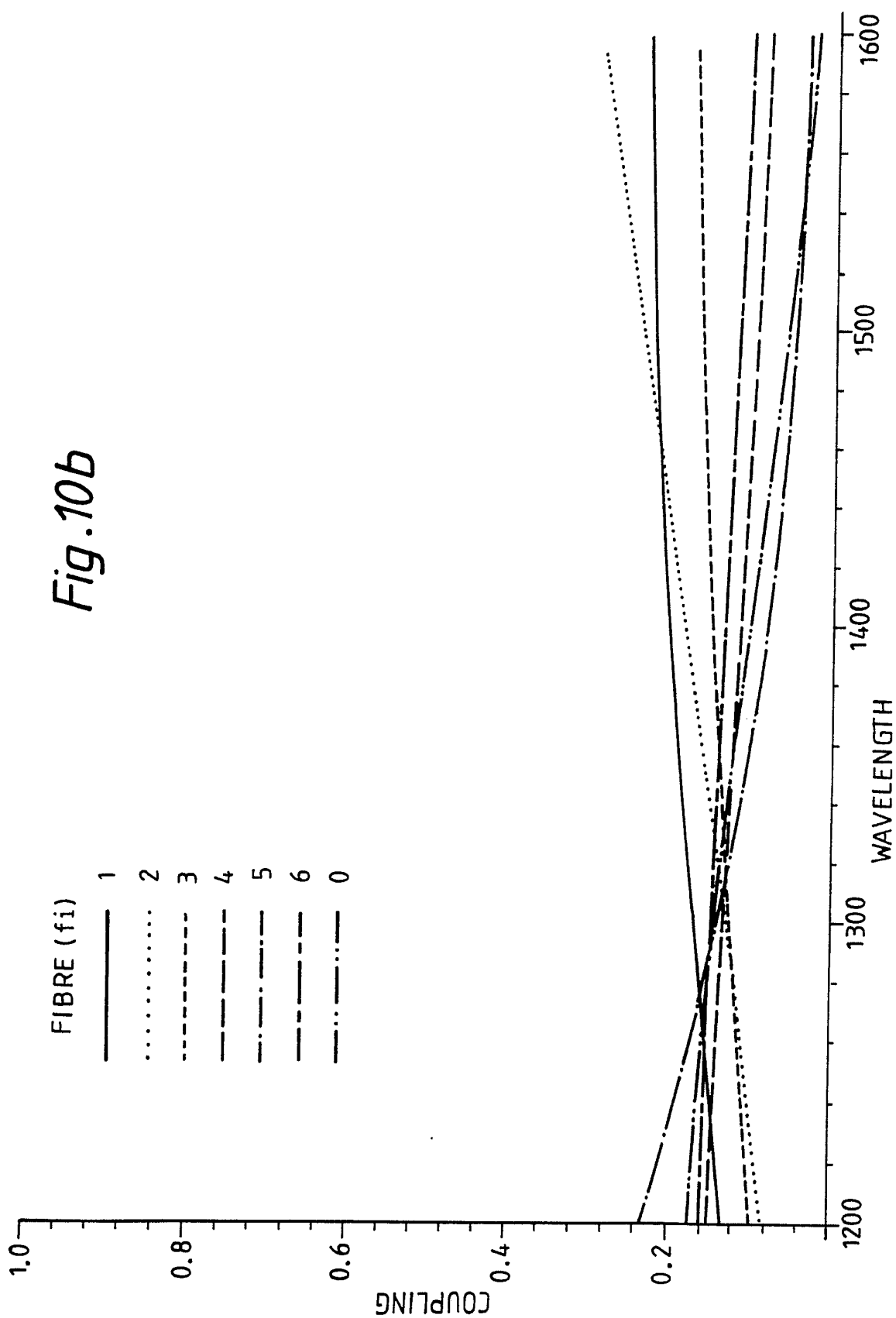
**Fig.5**

$\gamma = 0.44$

**Fig.6**

$\gamma = 1$

**Fig.7**

$\gamma = 0$
$\gamma = 1$

4/7

## Fig.8a



$P_1$

$P_i$, $i \neq 1$

0.5
0.4
0.3
0.2
0.1

1.3    1.4    1.5    1.6

## Fig.8b



$P_0$

$P_r$

0.5
0.4
0.3
0.2
0.1

1.3    1.4    1.5    1.6

5/7

## Fig.9a



## Fig.9b



## Fig.11

6/7

Fig.10a

FIBRE ( fi )

1
2
3
4
5
6
0

COUPLING

1.0

0.8

0.6

0.4

0.2

1200    1300    1400    1500    1600

WAVELENGTH

7/7

# Fig.10b

FIBRE (fi)

1 ———
2 ·········
3 ------
4 — — —
5 —·—·—
6 —··—··
0 —·—·—

COUPLING

1.0
0.8
0.6
0.4
0.2

1200   1300   1400   1500   1600

WAVELENGTH

# INTERNATIONAL SEARCH REPORT

**I. CLASSIFICATION OF SUBJECT MATTER**    (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl.5      C 03 B 37/15     G 02 B 6/28

**II. FIELDS SEARCHED**

Minimum Documentation Searched[7]

| Classification System | Classification Symbols |
|---|---|
| Int.Cl.5 | G 02 B 6/00    C 03 B 37/15 |

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched[8]

**III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]**

| Category[o] | Citation of Document,[11] with indication, where appropriate, of the relevant passages[12] | Relevant to Claim No.[13] |
|---|---|---|
| A | Applied Optics, vol. 29, 20 January 1990, Optical Soc. of America, New York, US; D.B. Mortimore: "Theory and fabrication of 4 x 4 single-mode fused optical fiber couplers", pages 371-374, see the whole article | 1,2,6,8 ,9 |
| A | Patent Abstracts of Japan, vol. 13, no. 9 (P-811)[3357], 11 January 1989, & JP,A, 63217314 (NIPPON TELEGR. AND TELEPH. CORP.) 09 January 1988, see the abstract | 1,2 |
| A | EP,A,0171479 (MAGNETIC CONTROLS CO.) 19 February 1986, see figure 1; abstract | 1,4 |
| A | EP,A,0287925 (LICENTIA) 26 October 1988, see the whole document      -/- | 1,7 |

[o] Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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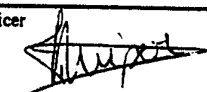
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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

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"&" document member of the same patent family

**IV. CERTIFICATION**

| Date of the Actual Completion of the International Search | Date of Mailing of this International Search Report |
|---|---|
| 24-10-1991 | 1 9 NOV 1991 |

| International Searching Authority | Signature of Authorized Officer |
|---|---|
| EUROPEAN PATENT OFFICE | Mme N. KUIPER |

| Category ° | Citation of Document, with indication, where appropriate, of the relevant passages | Relevant to Claim No. |
|---|---|---|
| | **III. DOCUMENTS CONSIDERED TO BE RELEVANT**     (CONTINUED FROM THE SECOND SHEET) | |
| A | Electronics Letters, vol. 25, no. 9, 27 April 1989, Stevenage, Herts, GB; D.M. Mortimore et al.: "Monolithic wavelength-flatttened 2 x 7 single-mode fused coupler", pages 606-607, see the whole article<br>----- | 1 |

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 08/11/91
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| Patent document cited in search report | Publication date | Patent family member(s) | | Publication date |
|---|---|---|---|---|
| EP-A- 0171479 | 19-02-86 | None | | |
| EP-A- 0287925 | 26-10-88 | DE-A- | 3713658 | 17-11-88 |
| | | US-A- | 4836644 | 06-06-89 |