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Miller et al.

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[54] REDUCTION OF DISPERSION IN MULTIMODE WAVEGUIDE

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[21] Appl. No.: **75,383**

[52] **U.S. Cl.** .....**350/96 WG,** 65/1, 65/DIG. 7
[51] **Int. Cl.** **G02b 5/14**
[58] **Field of Search** .....350/96 WG; 333/21

[56] **References Cited**

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Marcatili " What Kind of Optical Fiber for Long-Distance Transmission" S.P.I.E. Journal Vol. 8, No. 4, May, 1970, pp. 101–106.

Marcuse et al. " Mode Conversion Caused by Diameter Changes of a Round Dielectric Waveguide" The Bell System Technical Journal Vol. 48, No. 10, Dec. 1969, pp. 3,217–3,232.

Primary Examiner—John K. Corbin
Attorney—R. J. Guenther and Arthur J. Torsiglieri

[57] **ABSTRACT**

Dispersion in multimode optical waveguides is due primarily to the fact that the different modes propagate at different group velocities. Traditionally, the approach has been to try to minimize mode conversion and, thereby, to avoid the associated dispersive effect. An alternative approach is now suggested which deliberately increases the mode conversion opportunities along the wavepath such that the energy is forced to propagate an equal length of time in all the different modal configurations. This has the unexpected effect of reducing the dispersion since all the energy tends to arrive at the output more nearly at the same average time.

4 Claims, 5 Drawing Figures

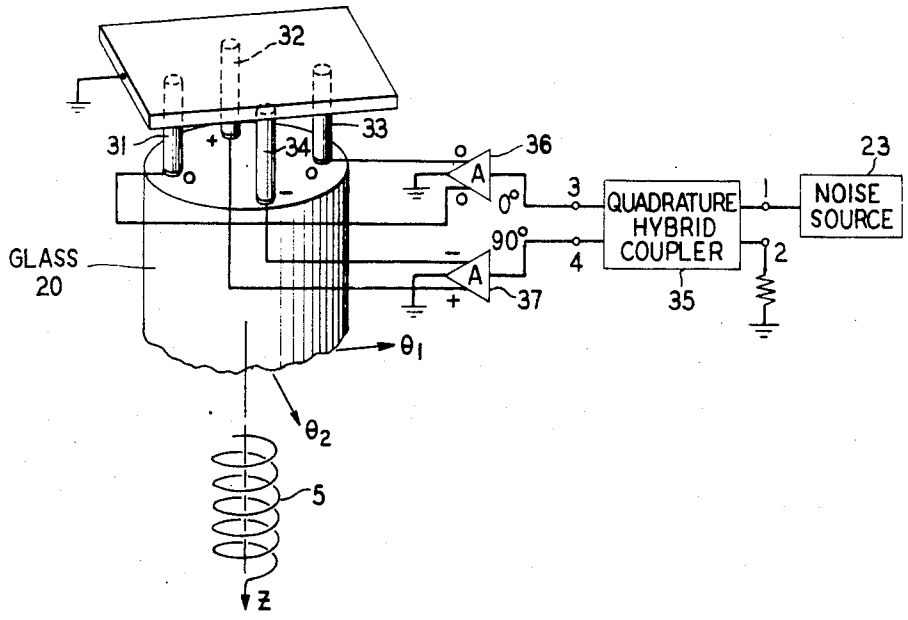


FIG. 1

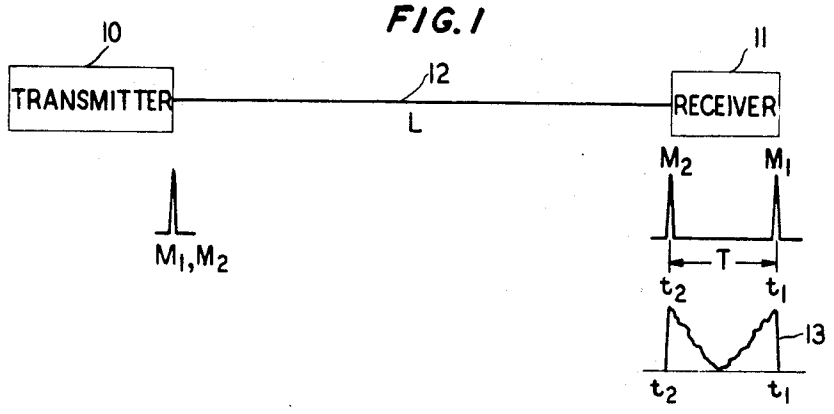


FIG. 2

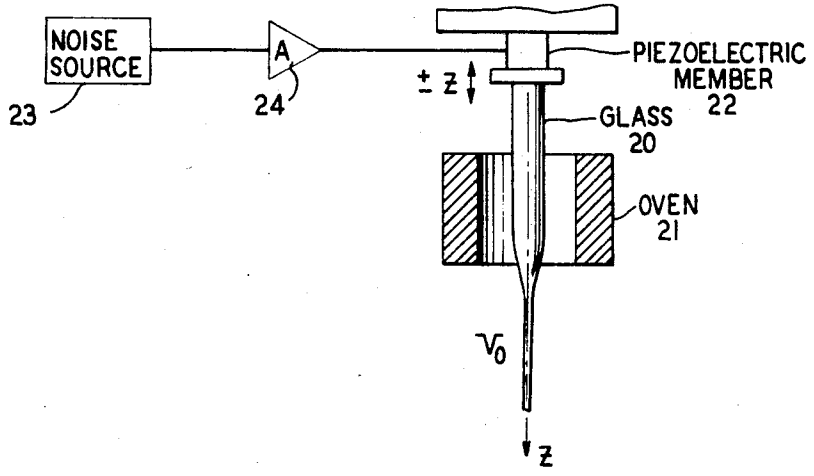
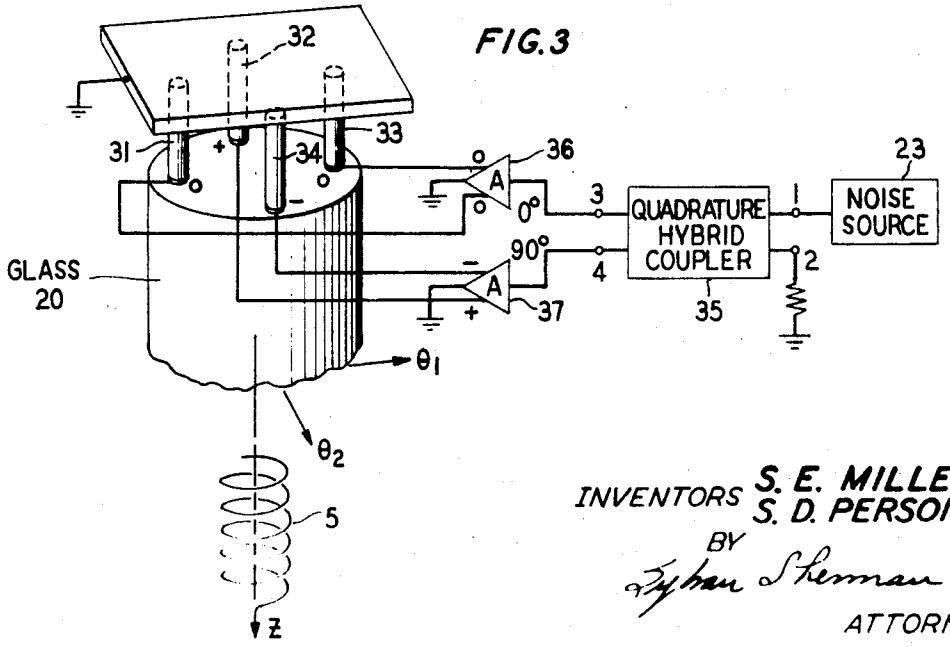


FIG. 3



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FIG. 4

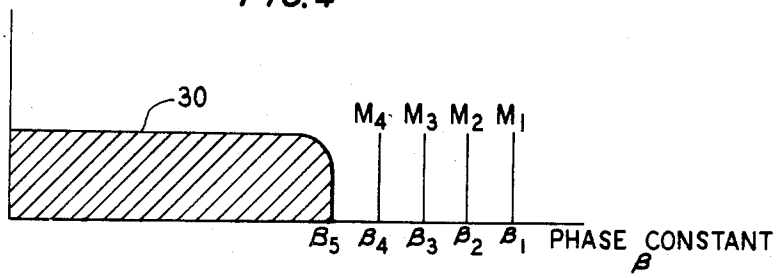
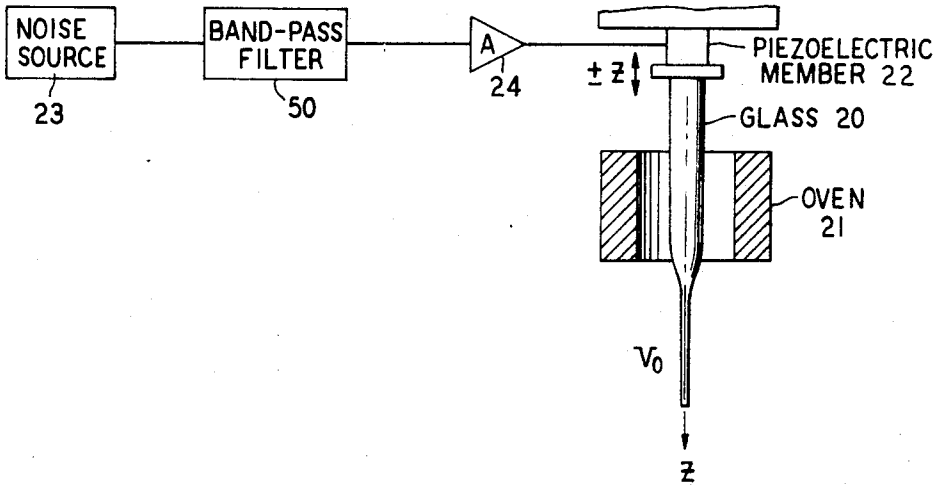

30
M4 M3 M2 M1
β5 β4 β3 β2 β1
PHASE CONSTANT
β

FIG. 5


NOISE SOURCE
23
BAND-PASS FILTER
50
A
24
± z
PIEZOELECTRIC MEMBER 22
GLASS 20
OVEN 21
V0
z

REDUCTION OF DISPERSION IN MULTIMODE WAVEGUIDE

This invention relates to multimode waveguides and, in particular, to optical waveguides.

BACKGROUND OF THE INVENTION

In the transmission of electromagnetic wave energy through a hollow conductive pipe or other type of waveguide, it is well known that the energy can propagate in one or more transmission modes, or characteristic field configurations, depending upon the cross-sectional size and shape of the particular guide, and upon the operating frequency. Typically, at any given frequency, the larger the guide size, the greater are the number of modes in which the energy can propagate. Generally, it is considered desirable to confine propagation to one particular mode chosen because its propagation characteristics are favorable for the particular application involved, and because propagation in more than one mode can give rise to power loss, conversion-reconversion distortion and other deleterious effects.

If the desired mode happens to be the so-called dominant mode, and the wavelength of the wave energy is large enough, it is feasible to restrict the cross-sectional dimensions of the guide so that no modes other than the dominant mode can be sustained therein. This expedient is not applicable, however, if the desired mode is not the dominant mode, or if a guide of larger cross section is prescribed in order to minimize attenuation, or for any other reasons. However, because these oversized, or multimode waveguides, are inherently capable of propagating more than one mode, they have always been considered to be potentially troublesome. For example, inasmuch as the different modes travel with different group velocities, mode conversion introduces a relative delay in that portion of the signal that is coupled to the other propagating modes. This is most evident when pulses are transmitted, and results in a broadening of the output pulse by a factor that is proportional to the length of the wavepath.

In the past, every effort has been made to perfect the waveguide and, thereby, to minimize mode conversion. In a paper by H. E. Rowe and W. D. Warters, entitled "Transmission in Multimode Waveguide With Random Imperfections," published in the May 1962 issue of the Bell System Technical Journal, pp. 1,031 –1,170, the effects of random geometric imperfections on the transmission of the $TE_{01}°$ mode wave, propagating in a circular waveguide, are studied and tolerances for these imperfections defined.

Because of the unique field configuration of some modes, it is feasible to tailor the waveguiding structure in a manner to favor a preferred mode. As an example, in the microwave and millimeter wave portions of the frequency spectrum, the circular electric TE modes can be effectively decoupled from the spurious TM modes by the helical waveguiding configuration described in U.S. Pat. No. 2,848,695.

The advent of the laser as a source of coherent radiation at optical wavelengths has substantially magnified the problems of guiding electromagnetic wave energy. Because of the extremely small wavelengths involved, none of the techniques considered above have provided a practical means of obtaining efficient transmission. Instead, new approaches and new techniques have been proposed for dealing with the problems of multimoding, as illustrated by the commonly assigned copending application by E. A. J. Marcatili, Ser. No. 59,014, **filed July** 28, 1970.

All of the approaches to this problem, heretofore considered, have either attempted to restrict propagation to only one mode, or to perfect the waveguide so as to minimize coupling from the preferred mode to other spurious modes.

Recognizing that it will be impractical if not impossible to eliminate all causes of mode conversion, it is the broad objective of the present invention to improve transmission through multimode waveguiding structures by other means.

SUMMARY OF THE INVENTION

In accordance with the present invention, it is shown that the dispersion in an unavoidably imperfect multimode waveguide can be reduced by deliberately enhancing the mode conversion processes in the waveguide. Accordingly, in one embodiment of the invention, random "imperfections" are deliberately introduced into the waveguide. These include changes in the cross-sectional dimensions of the guide and/or changes in the direction of the guide axis.

The inclusion of these discontinuities tends to more effectively couple the wave energy among the various modes. The greater this coupling, the more nearly all the energy will be distributed among all the possible modes and, as a result, the time it takes for all of the energy to traverse the guide is more nearly the same. Thus, whereas a pulse of energy propagating along an ideal waveguide in two different modes will arrive at the output end of the guide as two pulses, separated in time by an interval proportional to the length of the guide, the same energy pulse, propagating along a guide of equal length, designed in accordance with the teachings of the present invention, will arrive at the output end as a single pulse whose energy is distributed among all the coupled modes and whose width is proportional to the square root of the product of the guide length and the coupling length. Since the latter decreases as the degree of mode-to-mode coupling increases, the resulting dispersion decreases correspondingly.

While random coupling among the modes tends to reduce the dispersion, it also tends to increase losses due to the coupling of some of the energy from guided to unguided (radiating) modes. Accordingly, in a preferred embodiment of the invention, the coupling is selectively restricted so as to couple primarily among the guided modes. This coupling can be continuous, or included at spaced intervals along the waveguide.

These and other features of the present invention will be more readily understood from the following detailed description, taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows, in block diagram, a long distance communication system, and the effect of mode conversion upon a propagating pulse;

FIGS. 2 and 3 show arrangements for producing diameter changes and axial directional changes in a glass fiber;

FIG. 4 shows the mode distribution in a waveguide; and

FIG. 5 shows a preferred arrangement for producing diameter changes in a glass fiber.

DETAILED DESCRIPTION

Referring to the drawings, FIG. 1 shows, in block diagram, a communication system comprising a signal transmitter **10**, a receiver **11**, and a waveguide **12** connecting the transmitter to the receiver. For the purposes of the following explanation, it is assumed that waveguide **12** is capable of supporting only two propagating modes M_1 **1** and M_2 whose group velocities v_1 and v_2 are different, and that guide **12** is an ideal guide in that there is no coupling between the two modes.

If a signal pulse in each of the two modes is applied, simultaneously, at the transmitter end of guide **12**, each mode will propagate along the guide independently of the other and arrive at the receiver end of the guide at a time determined by its group velocity. Propagating at a velocity v_1, the pulse in mode M_1 will arrive after a time t_1 equal to L/v_1, while the pulse in mode M_1 will arrive after a later time t_2 equal to L/v_2, where L is the guide length. The time difference, T, or the dispersion is equal to $t_2 - t_1$.

Because any practical guide is not perfect, there will, in fact, be some coupling between the two modes so that energy tends to arrive at the receiver distributed over the entire interval between t_1 and $t_2$producing an output pulse such as is given by curve **13**.

In a qualitative sense, the above is equally descriptive of what occurs when the waveguide is excited in only one mode, but additional modes are produced due to mode conversion along the guide. In either event, the dispersion, due to the different group velocities for the different modes, manifests itself by broadening of the pulse by an amount which is proportional to the length of the guide. Recognizing this, the thrust of the prior art has been directed to means for perfecting waveguides so as to minimize node conversion and, thereby, to reduce its deleterious effects, and to means for absorbing the energy in the undesired modes so as to minimize the interval over which reconversion could occur.

The present invention is based upon an entirely new insight into the operation of waveguide. In brief, applicants view a multimode waveguide as a multilane highway wherein traffic proceeds along the different lanes at different velocities, corresponding to the different group velocities for the several modes. In a prior art waveguide, the energy in each of different modes tends to remain within one of the lanes (modes) throughout the length of the guide, with an occasional brief excursion (conversion) into one of the other lanes (modes). For the most part, however, the energy in prior art waveguides tends to remain primarily in its initial modal configuration and to travel at a particular velocity, arriving at the end of the guide at a different time than the small amount of energy that has inadvertently been converted into some other modes.

By contrast, in a waveguide in accordance with the present invention, there is a deliberate interchange of lanes, in that the energy in each mode is converted to each of the other modes and, hence, ultimately all of the energy propagates at all of the different mode velocities. Thus, on the average, energy initially launched, or converted to each of the supported modes, propagates at each of the other mode velocities, such that the energy in all of the modes tends to arrive at the output end of the guide more nearly at the same time. Qualitatively, it can be shown that the resulting pulse width T of an input impulse is given by

$$T \alpha \sqrt{LL_c} \qquad (1)$$

where L is the guide length
and L_c is the coupling length.

Since L_c is inversely proportional to the mode coupling per unit length, the greater the coupling, the smaller L_c and the narrower the output pulse.

FIG. 2 shows an arrangement for fabricating a glass fiber waveguide for guiding optical wave energy. Typically, such fibers are drawn from a bulk material by heating the glass in an oven and then pulling on it. Thus, in FIG. 2 a piece of glass **20** extends into an oven **21** and is drawn down at a velocity v. Since the diameter of the drawn fiber is a function of the velocity at which it is drawn, the velocity, in accordance with the prior art, is carefully controlled in order to obtain a uniform fiber. This uniformity has always been considered to be important since it was also known that variations in the fiber diameter induce mode coupling. By contrast, in accordance with the present invention, the velocity at which the glass is drawn is deliberately modulated so as to create diameter changes and, thereby, to enhance this coupling. Thus, in FIG. 2, the glass is supported by a piezoelectric member **22** which is energized by a signal derived from a noise source **23**. An amplifier **24** may be included to provide additional drive, if required.

In operation, the piezoelectric member produces an axial displacement $\pm\Delta z$ of glass **20** in response to the signal derived from the noise source. This displacement produces a change in the drawing velocity which, in turn, modulates the fiber diameter.

The modal configurations can, generally, be divided into two classes. The first class is characterized by field configurations that are symmetric about the guide axis. The second class is characterized by asymmetric field configurations. While changes in the diameter of the fiber enhances the coupling among the modes in the respective classes, it does not provide for efficient coupling between the two classes of modes. The latter is effectuated by changes in the direction of the guide axis. In a system supportive of wave energy polarized only along one direction, a ripple is induced in the waveguiding structure in the plane of the guide perpendicular to the direction of polarization. In a circular symmetrical guide, supportive of wave energy polarized along mutually perpendicular direction, ripples are induced in two mutually perpendicular directions, resulting in a helical waveguiding configuration. These directional changes are produced by a modification of the pulling structure of FIG. 2. As illustrated in FIG. 3, the piezoelectric member **22** of FIG. 2 is replaced by four piezoelectric rods **31**, **32**, **33** and **34**, symmetrically disposed about the longitudinal axis of the glass rod **20**. The rods are energized in pairs, 180° out of phase, and each pair is energized 90° out of phase relative to the other pair. To generate these signals, the signal derived from noise source **23** is cou-

pled to port 1 of a quadrature hybrid coupler 35 which divides it into two equal components in output ports 3 and 4. As is characteristic of a quadrature coupler, the two output signals are, in addition, 90° out of phase relative to each other.

Each of the two output signals, derived from ports 3 and 4, is coupled respectively to a different amplifier 36 and 37. The amplifiers, in addition to amplifying the signals, converts them to a pair of balanced signals which are used to energize diametrically opposite pairs of rods. Thus, the output signals from amplifier 36 are coupled to rods 31 and 33, while the output signals from amplifier 37 are coupled to rods 32 and 34.

While the total effect upon the glass pulling operation is a superposition of the effects produced by all the different frequency signal components derived from noise source 23, for purposes of explanation, the action of only one frequency component will be considered. In particular, the instant at which the signal component at amplifier 36 is zero is illustrated in FIG. 3. Simultaneously, the signal at amplifier 37 is a maximum, with a positive polarity signal applied across rod 32 and negative polarity signal applied across rod 34. The effect produced thereby is to induce an angular displacement of the glass axis by an amount θ_2, in the plane of the rods. A quarter of a cycle later, the signal at amplifier 37 is zero while the signal at amplifier 36 is a maximum, producing an angular displacement θ_1 in the plane of rods 31 and 33. This process continues, producing a deflection-θ_2 the next quarter cycle and a deflection-θ_1 a quarter cycle thereafter. The overall effect is to generate a helical motion as the glass is drawn, as indicated by curve 5 in FIG. 3. To induce both changes in diameter as well as changes in the direction of the guide axis, a common signal can be superimposed upon the four rods, or a separate piezoelectric member, separately excited, can be employed. With either arrangement, the modes within each of the two classes of modes are coupled among themselves as a result of the diameter changes, while interclass coupling is produced by changes in the direction of the fiber axis.

The use of a noise source, as in FIGS. 2 and 3, produces random intermodal coupling over the entire spectrum of modes. Unfortunately, however, this includes the unguided modes as well as the guided modes. While the latter continue to propagate along the guide and are conserved, the unguided modes radiate energy and constitute a loss to the system. It is apparent that in a guide of any appreciable length, all the energy would eventually be lost unless means are provided to prevent such coupling. Accordingly, in a preferred embodiment of the invention, selective, rather than random mode coupling is employed.

FIG. 4, included for purposes of explanation, shows a typical mode distribution in a waveguide as a function of phase constant. In general, there is a distribution of discrete guided modes M_1, M_2, M_3 and M_4, having phase constants β_1, β_2, β_3 and β_4, respectively. There is, in addition, a continuum of radiating modes starting at a phase constant β_5 that is less than the phase constants of the guided modes, as represented by the area bounded by curve 30.

In the random coupling arrangement described hereinabove, there is coupling both among the guided modes, producing a useful result, and among the guided and unguided modes, resulting in a loss to the system. Accordingly, in a preferred embodiment of the invention, the coupling is, advantageously, limited to only the guided modes by going from a random to a deterministic coupling arrangement. Since coupling will only occur between those modes whose beat wavelength λ_b approximates the spacial periodicity λ_m of the coupling mechanism along the wavepath, the mode conversion process can be more carefully controlled by restricting these spacial wavelengths to within those bands of wavelengths which permit coupling primarily to guided modes and, thereby, to minimize coupling to the unguided modes. Thus, to couple among all of the guided modes indicated in FIG. 4, the spacial wavelengths of the coupling means are confined to approximately ±10 percent of

$$\lambda_{12}=\frac{2\pi}{\beta_1-\beta_2};\quad \lambda_{13}=\frac{2\pi}{\beta_1-\beta_3};\quad \lambda_{14}=\frac{2\pi}{\beta_1-\beta_4};\quad \lambda_{23}=\frac{2\pi}{\beta_2-\beta_3};\quad \lambda_{24}=\frac{2\pi}{\beta_2-\beta_4};\quad \lambda_{34}=\frac{2\pi}{\beta_3-\beta_4}. \tag{2}$$

FIG. 5 shows one arrangement for producing selective coupling in accordance with the preferred embodiment of the invention. This arrangement is basically the same as that shown in FIG. 2, modified to include a bandpass filter in the excitation circuit driving the piezoelectric member. Using the same identification numerals as in FIG. 2, the apparatus shown in FIG. 5 includes a piece of glass 20, secured at its upper end to piezoelectric member 22, and extending at its lower end into oven 21. The piezoelectric member is electrically energized by noise source 23 coupled thereto through bandpass filter 50 and, optionally, an amplifier 24.

As indicated hereinabove, the diameter of the drawn fiber is related to the pulling velocity. More particularly, the relationship between diameter and velocity is given by

$$\frac{d_2}{d_1}=\left(\frac{v_1}{v_2}\right)^n \tag{3}$$

where n is approximately equal to one-half. Substituting this value for n in equation (3) gives

$$\frac{d_2}{d_1}=\left(\frac{v_1}{v_2}\right)^{1/2} \tag{4}$$

The instantaneous displacement, z, produced by the piezoelectric member, at a frequency ω is

$$z=z_p \sin \omega t, \tag{5}$$

where z_p is the peak displacement, which varies as a function of the amplitude of the electrical excitation.

The incremental velocity v_m superimposed on the fiber is given by the time derivative of the displacement, or $v_m = dz/dt = z_p\omega \cos \omega t = v_{mp} \cos \omega t$. (6)

The instantaneous fiber drawing velocity is then given by

$$v = v_o + v_m, \quad (7)$$

where v_o is the average pulling velocity.

For an increase in diameter 2a in a fiber having an average diameter 2d, the ratio of the peak velocity to the average velocity is

$$\frac{v_o + v_{mp}}{v_o} = \left(\frac{d+a}{d}\right)^2 \approx 1 + \frac{2a}{d} \quad (8)$$

for

$$a/d << 1.$$

From (8), we derive

$$v_{mp} = \frac{2a}{d} v_o \quad (9)$$

Substituting for v_{mp} from Equation (9), and solving for z_p, we obtain

$$z_p = 2\frac{a}{d}\cdot\frac{v_o}{\omega} = \frac{1}{\pi}\cdot\frac{a}{d}\cdot\lambda_m \quad (10)$$

where

$\lambda_m = v_o/f$ is the mechanical or spacial wavelength of the diameter change along the fiber introduced by the electrical drive signal of frequency f.

Thus, knowing both the desired beat wavelengths, λ_b, from Equations (2), and the average drawing velocity, v_o, the spacial wavelengths, λ_m, of the diameter changes and the drive signal frequencies are defined.

As a numerical example, we assume a fiber having a diameter $2d = 6$ μm, being drawn at average rate of 2 ft/sec or 0.61 m/sec. Using Table I on page **3203** of the article by D. Marcuse entitled "Mode Conversion Caused by Surface Imperfections of a Dielectric Slab Waveguide," published in the December 1969 issue of the *Bell System Technical Journal*, we find that we can obtain one hundred percent coupling between modes with a coupling length D equal to 30,000 μm for a change in fiber radius a when $a = (40 \cdot (3)^2)/(30{,}000) = 0.012\mu m$.

The constant **40** used above is an approximation of the values given in the column headed ad/d^2 in Table I of the above-identified article for a refractive index difference between the fiber core and its cladding of 1 percent; i.e., $n_g = 1.01$.

For any particular beat wavelength λ_b, which is a function of the signal frequency and the fiber diameter, the longitudinal displaced z_p that must be produced can now be computed using Equation (10). From the relationship

$$f = v_o/\lambda_m, \quad (11)$$

we can also compute the optimum frequency of the drive signal. Assuming a beat wavelength of 200 μm, the drive signal frequency is approximately 3,000 Hertz. Thus, bandpass filter **50** has one passband centered at 3,000 Hertz, and amplifier **24** delivers enough voltage to piezoelectric member **22** to produce a peak-to-peak longitudinal displacement of ± 0.25μm. A similar calculation is then performed for all the other pairs of modes, thus fully defining the passband characteristic of filter **50** and amplifier **24**.

A similar analysis can be carried out to produce directional changes in the guide axis for coupling between classes of modes, if required.

It should be noted that there may be an overlapping of beat wavelengths so as to couple between some of the unguided modes. That is, the beat wavelengths calculated from Equations (2) may result in coupling between modes M_1, M_2, M_3 and M_4, and inadvertently among some unguided modes within curve **30**. This, however, will be significantly less than the degree of coupling that would be obtained if the coupling was purely random.

While the invention has been described in connection with glass fibers for guiding optical waves, the principles of the invention are equally applicable in connection with millimeter and microwave guidance systems. Thus, in all cases it is understood that the above-described arrangements are illustrative of but a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

We claim:

1. In an electromagnetic wave system, a waveguide capable of guiding optical wave energy at the frequency of interest in a plurality of different modes of wave propagation having different group velocities and of dissipating wave energy in the form of unguided modes;

means for minimizing dispersion due to said difference in group velocities comprising means longitudinally distributed along said guide for enhancing the coupling among said guided modes while minimizing the coupling among said guided modes and said unguided modes.

2. The waveguide according to claim 1 wherein said means includes changes in the diameter of said waveguide.

3. The waveguide according to claim 1 wherein said means includes changes in the direction of the guide axis.

4. The waveguide according to claim 1 wherein said means has a periodic variation equal to the sum of the beat wavelengths of pairs of all the guided modes, plus or minus ten percent.

* * * * *

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,687,514 Dated August 29, 1972

Inventor(s) S. E. Miller - Stewart D. Personick

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Col. 3, line 13, change "M_1I" to --M_1--;

3, line 24, change "M_1" to --M_2--;

line 43, change "node" to --mode--.

Signed and sealed this 6th day of March 1973.

(SEAL)
Attest:

EDWARD M.FLETCHER,JR.
Attesting Officer

ROBERT GOTTSCHALK
Commissioner of Patents

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