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Rowe et al.

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[54] MULTIMODE WAVEGUIDE WITH REDUCED DISPERSION

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[58] Field of Search... 333/95, 98 M, 98; 350/96 WG, 350/96

[56] References Cited

UNITED STATES PATENTS

3,157,726	11/1964	Hicks, Jr. et al.	333/95 X
3,259,903	7/1966	Lerner.	333/98 X

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[57] ABSTRACT

Transmission performance of a multimode waveguide is optimized (i.e., pulse dispersion is minimized) by optimizing the coupling among the different modes. More specifically, in a waveguide supportive of modes having group velocities v_1 and v_2 , and wherein the coupling mechanism comprises random discontinuities having an essentially white spectrum, optimum coupling is defined by an optimum coupling length L_{opt} given by

$$L_{opt} = k \cdot f,$$

where f is the midband signal frequency and

k is a constant equal to

$$\frac{1}{\pi f^2 \left(\frac{1}{v_2} - \frac{1}{v_1} \right)}$$

4 Claims, 4 Drawing Figures

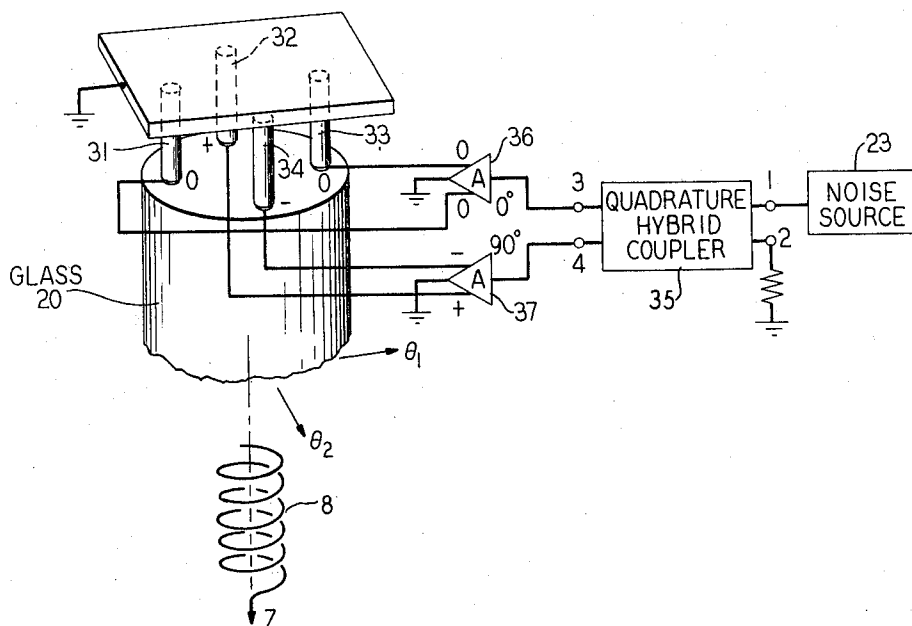
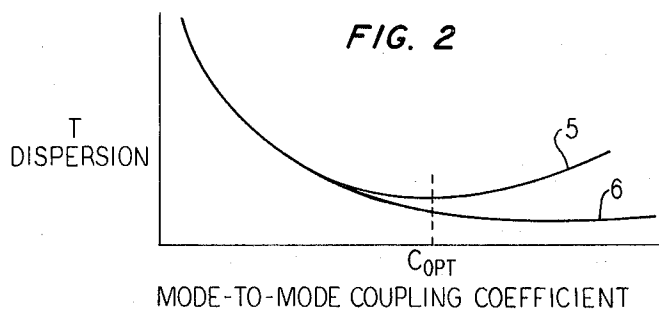
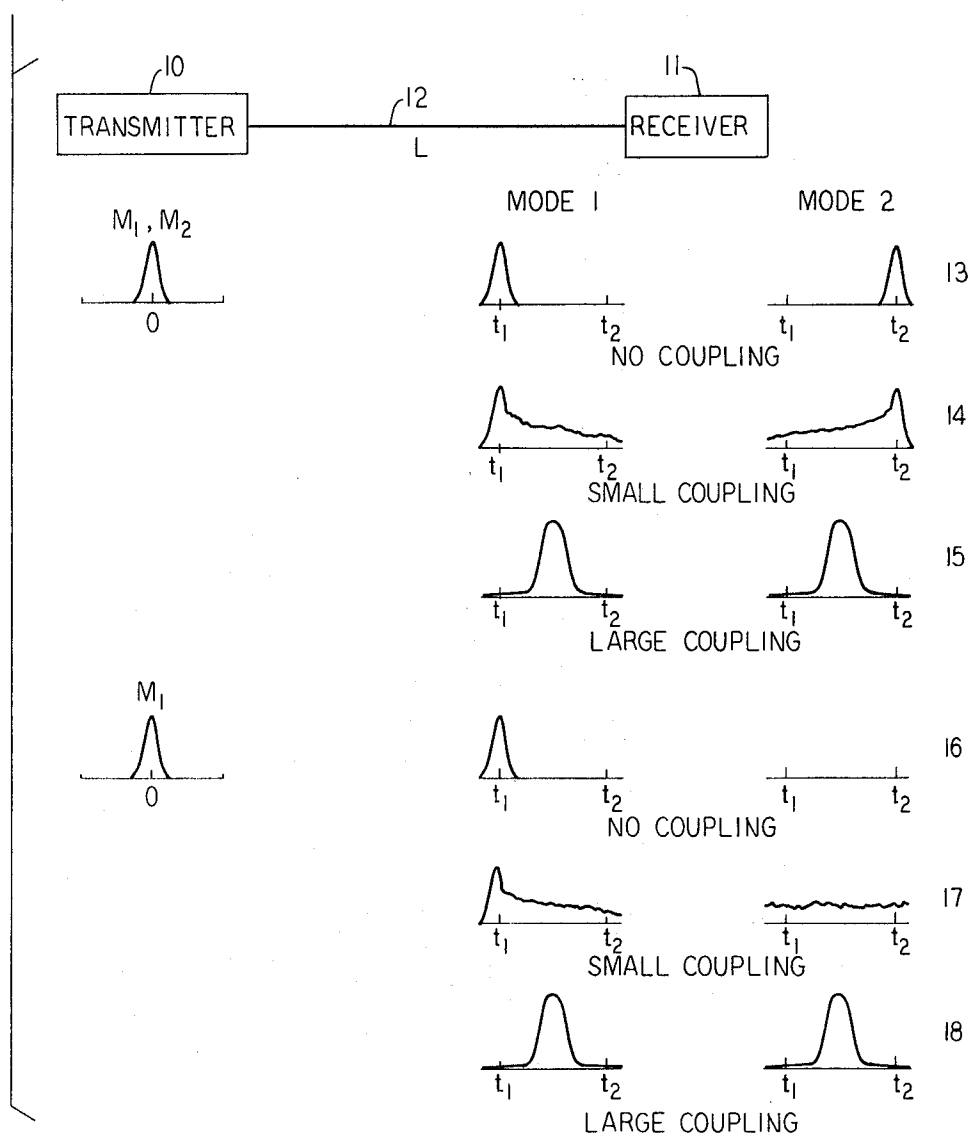


FIG. 1



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FIG. 3

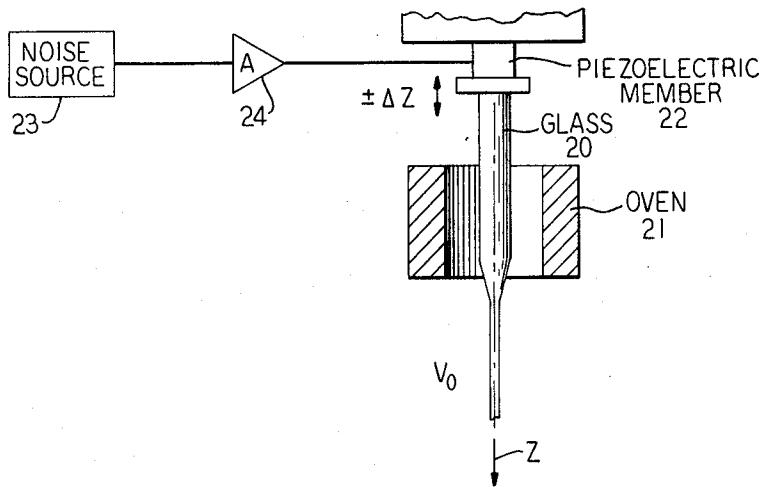
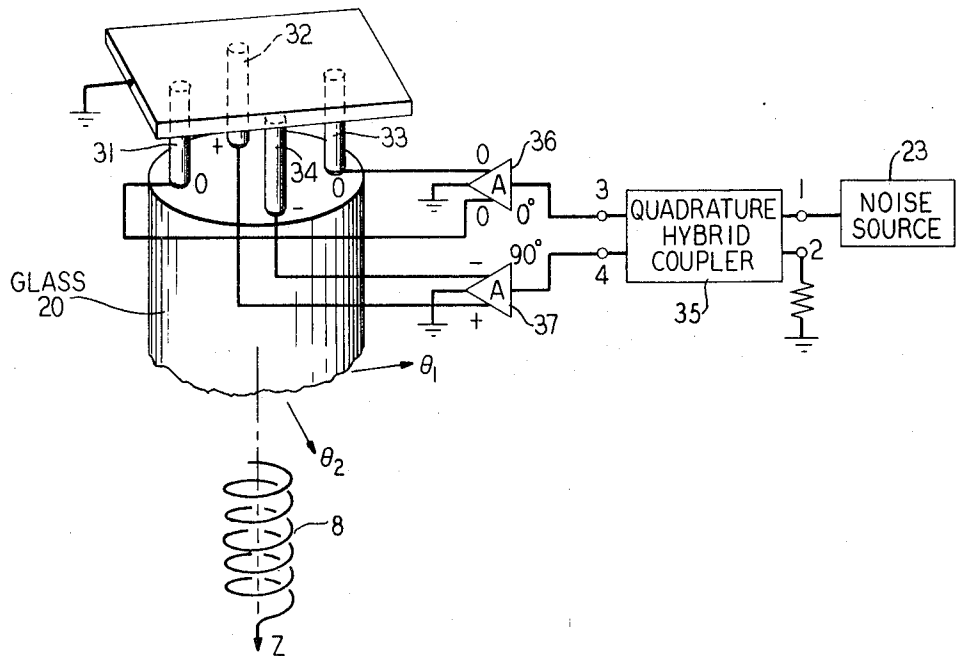


FIG. 4



MULTIMODE WAVEGUIDE WITH REDUCED DISPERSION

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.

In the past, every effort has been made to perfect the waveguide and, thereby, to minimize mode conversion. More recently, however, S. E. Miller and S. D. Personick, in their U.S. Pat. application Ser. No. 75,383, filed Sept. 25, 1970, now U.S. Pat. No. 3,687,514, issued Aug. 29, 1972, and assigned to applicants' assignee, have shown that pulse dispersion in a multimode waveguide, due to differences in the velocities of mode propagation, can be reduced by deliberately increasing the mode conversion opportunities along the waveguide. As indicated by Miller et al., this has the unexpected effect of reducing the pulse dispersion since all the energy tends to arrive at the output more nearly at the same average time.

For the purpose of their analysis, Miller et al. assumed that the coefficients of coupling among the various modes were frequency independent over the band of interest. However, for coupling mechanisms that arise from small departures from a perfect waveguide (i.e., slight diameter variations, straightness deviations, ellipticity, et cetera) the coupling coefficient varies approximately inversely with frequency.

It is, accordingly, the object of the present invention to minimize pulse dispersion in a multimode waveguide wherein the coefficient of coupling between modes varies inversely as a function of frequency.

SUMMARY OF THE INVENTION

In accordance with the present invention, the transmission performance of a multimode waveguide is optimized by optimizing the intermodal coupling. More specifically, in a waveguide supportive of two different modes, and wherein the coupling mechanism comprises random discontinuities having an essentially white spectrum, the amount of coupling can be specified by a characteristic length L_c called the coupling length, which is inversely proportional to the coupling intensity. In physical terms, this is the length in which the average power, injected in either mode, becomes approximately equally divided between the two modes (assuming the heat losses for the two modes are approximately the same). The optimum coupling length, L_{opt} , for minimum pulse dispersion, is given by

$$L_{opt} = k \cdot f$$

(1)

where

f is the mid-band signal frequency;

k is a constant equal to

$$\frac{1}{\pi f^2 \left(\frac{1}{v_2} - \frac{1}{v_1} \right)}$$

and

v_1 and v_2 are the group velocities of the two modes and are functions of the geometric and material parameters of the guide. $(1/v_2) - (1/v_1)$ varies approximately inversely as the frequency squared.

It is a feature of the invention that this optimum coupling is independent of the length of 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;

FIG. 2, included for purposes of explanation, show the variations in dispersion as a function of mode-to-mode coupling; and

FIGS. 3 and 4 show arrangements for producing diameter changes and axial directional 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 and M_2 whose group velocities v_1 and v_2 are different.

In the first case, now to be considered, we further assume that guide 12 is a perfect waveguide, i.e., that there is no coupling between the modes. If, in this case, 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 will 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_2 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 $t_2 - t_1$. Curve 13 shows the resulting outputs for the two modes.

Because any practical guide is not perfect, there will, in fact, be some coupling between the modes so that the energy in each mode tends to arrive at the receiver distributed over the entire interval between t_1 and t_2 , as indicated by curves 14 for the case of small coupling.

Similar behavior is observed when the waveguide is excited in only one of the modes. This is illustrated by curves 16 and 17 which show, respectively, the case of a perfect guide excited by mode M_1 and the case of a guide, with small coupling, excited by mode M_1 .

It will be noted that for small coupling in either case of excitation, (i.e., in one or in both modes,) the dispersion manifests itself by a 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 mode 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 can occur.

In their above-identified application, S. E. Miller et al., note that a multimode waveguide can be viewed as a multilane highway wherein traffic proceeds along with different velocities, corresponding to the different group velocities for the several modes. In the typical prior art waveguide, the energy in each of the 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) and return (reconversion) to the original lane (mode). 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 teaching of Miller et al., 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. For the two mode case, curves 15 and 18 illustrate, respectively, the outputs for excitation in both modes, and in mode M_1 , for a guide with large coupling. As can be seen, the dispersion is much less than $t_2 - t_1$. In the particular case where the mode-to-mode coupling mechanism is frequency-independent, it can be shown that the resulting dispersion is given by

$$T \propto \sqrt{LL_c} \quad (2)$$

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 is L_c and the less the dispersion.

The present invention is based upon the recognition that the mode-to-mode coupling will not be frequency-independent and, consequently, there is a limit upon the improvement that can be obtained by increasing the mode-to-mode coupling. More importantly, however, an optimum mode-to-mode coupling is defined. In particular, for small departures from a perfect waveguide (such as slight diameter variations, straightness deviations, ellipticity, et cetera) the coupling coefficients vary approximately inversely with frequency. For this case, applicants have discovered explicit relations for the desired optimum coupling and the attendant best performance of the waveguide. This is illustrated graphically in FIG. 2, which shows the

variation in the dispersion T as a function of the mode-to-mode coupling. In particular curve 6, illustrative of the case wherein the coupling coefficient is independent of frequency, shows a continuing decrease in the dispersion as the coupling coefficient increases. Curve 5, illustrative of the case wherein the coupling coefficient is inversely proportional to frequency, is concave upward, with a minimum value for the dispersion at an optimum coupling C_{opt} . In particular, for the two mode case with random coupling, optimum coupling is obtained when the characteristic coupling length is given by

$$L_{opt} = \frac{1}{\pi f \left(\frac{1}{v_2} - \frac{1}{v_1} \right)} \quad (3)$$

where

L_{opt} is the optimum length within which the average power, injected in either mode, becomes approximately equally divided between the two modes (assuming the heat losses for the two modes are about the same;

v_1 and v_2 are the group velocities for the two modes;

and

f is the carrier frequency.

It should be noted that this optimum coupling is independent of the actual length of the guide.

FIGS. 3 and 4, included for purposes of explanation, illustrate ways of obtaining random coupling in a glass fiber waveguide for use in guiding optical waves. Typically, such fibers are drawn from a bulk material by heating the glass in an oven and then pulling on it. Thus in FIG. 3 a piece of glass 20 extends into an oven 21 and is drawn down at a velocity v_0 . 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. 3, 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 in circular fibers can be divided into classes according to the order of the angular variations of the electromagnetic fields. The coupling between modes within the same class (same angular variation) can be accomplished by diameter variations of the type described above. The coupling between modes of adjacent classes (angular variations differing by one) can be accomplished by displacing the guide axis. These two types of coupling are generally sufficient in most cases of practical interest.

FIG. 4, now to be described, illustrates one way of producing axial displacements in two mutually perpen-

dicular directions for coupling between adjacent classes of modes in a circular fiber waveguide. As illustrated, the piezoelectric member 22 of FIG. 3 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 coupled 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. 4. Simultaneously, the signal at amplifier 37 is a maximum, with a positive polarity signal applied across rod 32 and a 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 $-\theta_2$ the next quarter cycle and a deflection $-\theta_1$ a quarter cycle thereafter. The overall effect is to generate a helical motion as the glass is drawn, as indicated by curve 8 in FIG. 4. To induce both changes in diameter as well as displacing the guide axis, a common signal can be superimposed upon the four posts, 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 transversely displacing the fiber axis.

As indicated hereinabove, the coupling can be characterized by a coupling length L_c which is inversely proportional to the strength of the coupling. Initially, unequally distributed powers in a two mode guide will tend to equalize after propagating along the guide a distance L_c if the difference between the heat losses for the two modes is negligibly small (a good approximation for optical fibers). Thus, L_c will depend upon the amplitude of the modulating signal applied to the piezoelectric members being used to induce the guide discontinuities. Since L_c is a function of the geometric and material parameters of the guide and the statistics of the imperfections, one could calculate the required diameter, or straightness deviation and, in turn, relate it to the signal amplitude. When this is done, it is found

that for smaller size optical fibers, optimum coupling is obtained for rms deviations of a few percent. For example, a 6 percent rms deviation produces optimum coupling in a 6 micron fiber. For larger size fibers, however, the percent deviation becomes too large to be practical. In this latter case, the frequency dependence of the coupling can be ignored since the realizable coupling will be less than optimum and, as can be seen in FIG. 2, curves 5 and 6 are essentially the same in the region below C_{opt} .

As a practical matter, the optimum coupling, and the signal necessary to produce it, can be determined experimentally by fabricating a number of fibers having different degrees of deviation, and then measuring and plotting the resulting dispersion. This gives rise to a curve, such as curve 5 in FIG. 2, from which a fair indication of the signal amplitude needed to produce optimum coupling can be obtained. In this connection it should be noted that since the optimum coupling is independent of guide length, the dispersion measurements can be made using any convenient guide length. Such a procedure can also be applied to guides for any number of modes.

An alternative method of producing coupling in a waveguide is to vary the dielectric constant both transversely and along the axis of the waveguide. Hence, various means and combinations of means can be employed to produce the desired intermodal coupling.

In the discussion hereinabove, reference has been made to two modes having two different group velocities. As a practical matter, a number of modes may have the same group velocity. Thus, more generally, the invention is applicable to any two groups of modes having two different group velocities.

While the invention has been described in connection with glass fibers for guiding optical waves, it will be recognized that 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 a waveguide capable of guiding wave energy at a frequency of interest f in a plurality of different modes of wave propagation having two different group velocities v_1 and v_2 :

random coupling means uniformly distributed along said guide for coupling wave energy among said different modes where;

said coupling varies substantially inversely as a function of frequency;

and where the coupling length is given by

$$L_{opt} = \frac{1}{\pi f \left(\frac{1}{v_2} - \frac{1}{v_1} \right)}$$

2. The waveguide according to claim 1 adapted to guide optical wave energy.

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

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4. The waveguide according to claim 1 wherein said coupling means includes changes in the position of the guide axis.

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