Interferometry through single-mode optical fibers

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Abstract

A single-mode optical fiber can be used as a leg of an interferometer, making possible new applications of interferometry. Since this kind of fiber does not allow higher-order modes to propagate, it acts as a spatial filter and provides a smooth wavefront at its output end. A practical method of providing optically good input and output faces for a fiber core only a few micrometers in diameter is described, including a means of stripping away cladding modes. The problem of coupling from a laser into a single-mode fiber is discussed, including optimal matching of a gaussian beam to the Bessel function field distribution of the HE_{11} mode. Theoretical coupling efficiency can be as high as 99.7 percent, and experimental efficiency is 70 percent, not corrected for Fresnel reflections. Experimental results are presented showing the change in the optical length of a fiber with temperature and the use of single-mode fibers in two types of interferometer, a Fabry-Perot etalon and an unequal-path Mach Zehnder interferometer with 128 meters of optical fiber in one of the paths.

Introduction

Development of optical fibers through which only a single spatial mode can propagate and in which the attenuation is very low has opened up new applications of interferometry. Because of the spatial filtering action of the fiber itself, imperfections tend to produce only loss of light without impairing the interferometric quality of the wavefronts. The flexibility of optical fiber and the low attenuation make it possible to wind many meters of optical path onto a spool and contain it in a small space. In addition, the chemical inertness, electrical nonconductance, small size, and light weight of fibers allow the precision of interferometry to be applied in new ways to many difficult instrumentation problems.

The most important application of fiber interferometry so far has been the fiber gyro ring interferometer, using the Sagnac effect.[1,2] Applications of similar techniques to sensing of temperature and pressure variations have also been reported.[3,4] These applications do not necessarily require the fibers to be single-mode, but this characteristic offers greater experimental convenience.

Although there are advantages to the use of single-mode fiber, there are also aspects that require special attention. Single-mode fibers are smaller in diameter, and more difficult to handle for that reason. The radiation that is injected into the end of the fiber must match the propagating mode with sub-micrometer precision, or much of it will be lost. Radiation that spills into the cladding at the input end or is scattered into it along the length of the fiber can degrade the quality of the transmitted wavefront, unless properly taken care of. One purpose of this paper is to clarify these problems and offer practical suggestions toward their solutions.

A second purpose of this paper is to describe two potential applications of single-mode fiber interferometry. First, we have constructed a Fabry-Perot etalon from a small piece of single-mode fiber. Such flexible fiber etalons may be more convenient for tunable fiber Raman and Brillouin lasers[5], and also for improved sensitivity in temperature and pressure sensing. Second, we have constructed an unequal-path Mach-Zehnder interferometer that can measure the frequency drift of a laser to high precision without requiring a stable local oscillator.

Single-Mode Fiber Characteristics

The optical fiber used for the measurements to be described was a Type T-110 step-index fiber with a 4.5 micrometer diameter fused-silica core 80-micrometer diameter glass cladding, manufactured by ITT. The wavelength used, 0.6328 micrometers, is below the cut-off of all of the higher-order modes of the fiber, so that only the HE_{11} mode, which has no cut-off, can propagate.

The HE_{11} mode has a transverse electric field distribution given by[6]

$$E = A\,J_0(\kappa r) \quad \text{for } r \le a$$

$$= A\sqrt{\frac{a}{r}}\,J_0(\kappa a)\,e^{-\gamma(r-a)} \quad \text{for } r \ge a \qquad (1)$$

where

$$\kappa^2 = \omega^2 \mu \epsilon_1 - \left(\frac{2\pi}{\lambda}\right)^2$$

$$\gamma^2 = \left(\frac{2\pi}{\lambda}\right)^2 - \omega^2 \mu \epsilon_2$$

a is the radius of the core, and ϵ_1 and ϵ_2 are the permittivities of the core and cladding, respectively. The distribution inside the core follows a Bessel function, while the field is exponential outside of the core. The two distributions match at the boundary between the core and the cladding.

Since only the HE_{11} mode can propagate in the fiber, the fiber acts as a mode filter. If a beam containing many spatial modes is incident on the end of the fiber, all of the radiation except that having a distribution similar to that of the HE_{11} mode will be rejected. The radiation arriving at the other end of the fiber will have a smooth intensity and phase distribution, regardless of the complexity of the wave at the input.

Although the core of the fiber acts as a mode filter, the radiation that is rejected from the core tends to become trapped in the cladding, which acts as a secondary waveguide for the radiation. To take advantage of the desirable features of the guiding properties of the core, therefore, it is necessary to eliminate the radiation carried by the cladding. The problems of coupling to the fiber and removing the cladding modes will now be discussed.

Coupling to Single-Mode Fiber

The field distribution of the HE_{11} mode is not gaussian, and because of this, it is not possible to match it perfectly to the distribution of a beam that can propagate outside of the fiber. There is nothing that can be done about this; Maxwell's equations do not have the same solutions in free space as they do in a fiber. Fortunately, the field distributions are quite similar, and good coupling can be achieved.

The efficiency of coupling from an external field into the fiber is defined as the fraction of the incident power that is successfully launched as a progagating mode in the fiber. It may be considered to be the product of the fraction of the incident power that is transmitted by the interface between the end of the fiber and the external medium and the fraction of this transmitted power that is coupled into the propagating mode of the fiber. These two fractions could be called the Fresnel efficiency and the mode-match efficiency. The Fresnel efficiency may be written

$$\eta_{Fresnel} = 1 - \left(\frac{n-1}{n+1}\right)^2 \qquad (2)$$

where n is the effective index of the fiber. The mode-match efficiency is[7]

$$\eta_{match} = \frac{\left[\int_A E_1 \; E_2 \; dA\right]^2}{\int_A E_1^2 \; dA \int_A E_2^2 \; dA} \qquad (3)$$

E_1 and E_2 are the two field distributions that are being matched. For example, E_1 could be the incident beam of radiation and E_2 the distribution of the mode it is desired to couple to. The mode in the fiber has constant phase in any transverse plane, and if the incident beam has its phase front tilted with respect to the transverse plane of the fiber, or if it is not a plane wave, the phase difference between the two fields in each element of area must be taken into account.

Equation 3 may be used to determine the mode-match efficiency that can be achieved between a gaussian beam and the propagating mode of a single-mode fiber. It is clear that the best efficiency will be obtained when the incident beam is a plane wave propagating in the direction of the axis. This means that the beam should have a waist at the entrance plane of the fiber. It is also intuitively clear that the best coupling efficiency results when the peak intensity of the gaussian beam coincides with the center of the fiber. It It remains to show how large the beam waist should be in relation to the diameter of the core for best coupling. To do this, Equation 3 was solved numerically with the HE_{11} mode distribution as E_2 and a gaussian distribution as E_1. The computed mode-match efficiency as a function of the waist radius is shown in Figure 1.

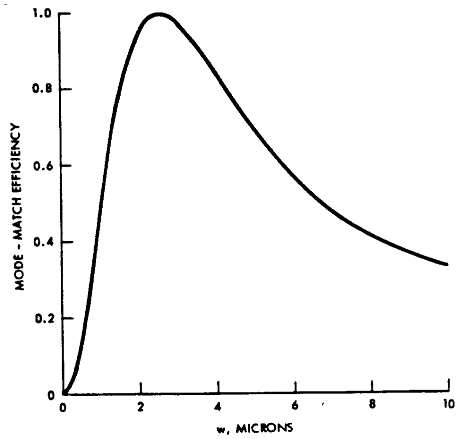

Figure 1. Mode-match efficiency of a centered, coaxial gaussian beam at 0.6328 micrometers with the HE_{11} mode of an ITT Type T-110 fiber, as a function of the waist radius.

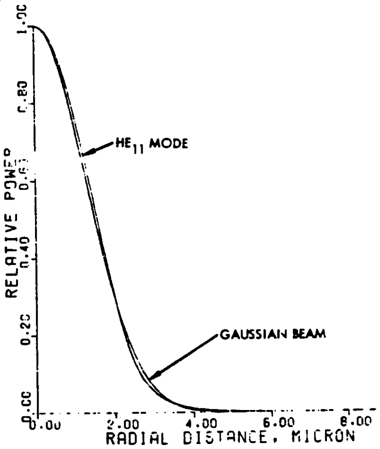

Figure 2. Electric field distributions of the HE_{11} mode in Type T-110 optical fiber and the gaussian beam at 0.6328 micrometers that gives optimal coupling efficiency. Core radius 2.25 micrometers.

It may be seen that very high mode-match efficiency (> 99%) may be achieved if the gaussian beam is the correct size in relation to the core, and that an error of 10% in the size of the waist causes only a slight drop in efficiency. A gaussian of the optimal size is plotted in Figure 2 for comparison with the distribution of the HE_{11} mode of the fiber.

It is also of interest to consider coupling to beams that are not circularly symmetric, such as beams radiated by single-mode injection lasers. The mode-match efficiency could be found from Equation 3 by substituting the field distribution radiated by the diode laser and integrating over the area of the fiber. This calculation could then be repeated for different magnifications of the beam to find the size that gives the best coupling. However, an approximate answer can be obtained without so much computation. Measured radiation patterns of injection lasers can be well approximated by the product of two gaussians along orthogonal axis in the transverse plane. Considering the very good match between a circularly symmetric gaussian beam and the HE_{11} mode of the fiber, a good estimate of the coupling between a single-mode diode laser and a single-mode diode laser and a single-mode fiber can probably be made by assuming the laser beam to be the product of two gaussians and the mode of the fiber to be gaussian also. If this is done, an approximate mode-match efficiency may be found without integrations, from

$$\eta_{match} = 4\left[\left(\frac{W_{1x}}{W_2} + \frac{W_2}{W_{1x}}\right)\left(\frac{W_{1y}}{W_2} + \frac{W_2}{W_{1y}}\right)\right]^{-1} \quad (4)$$

where the subscripts 1 and 2 refer to the incident beam and the fiber mode respectively, and x and y refer to orthogonal axes in the transverse plane, W is the gaussian radius. For a laser beam with an aspect ratio of 3, the optimal magnification gives an efficiency of about 75%.

Coupling Techniques

Because of the mode-filtering property of single-mode fibers, the propagating radiation has a uniform phase distribution, as it reaches the end of the fiber. However, if the optical quality of the interface between the core and the external medium is imperfect, the output phase front is modified and the quality of the radiation pattern from the fiber is reduced. At the input end, a poor interface modifies the incident phase front, resulting in a lower coupling efficiency than would otherwise be the case. Consequently, it is important to provide a high-quality interface at both ends of a single-mode fiber.

It is also desirable to ruggedize the fiber in some way so it may be easily handled, held in an optical mount, and aligned. Since the presence of a speck of dust in the middle of a beam of light less than 10 micrometers in diameter can drastically alter the radiation pattern, it is also important to be able to clean the fiber end without damaging it.

A practical method of achieving these objective is illustrated in Figure 3. The outer jackets of the fiber are first removed for about 7 cm of length on both ends of the fiber. The ends are cleaved by scribing and pulling gently, and are inspected under a microscope to verify that the cleaved surfaces are flat and perpendicular to the axis of the fiber. Each end is then inserted into a close-fitting capillary tube filled with index-matching epoxy. A small clean piece of microscope cover glass is placed over the end of the capillary tube in such a way that the space is filled with epoxy and air bubbles are excluded. The cleaved end of the fiber is then pushed against the cover glass, excluding as much epoxy as possible, and the assembly is allowed to harden. Fibers prepared in this way exhibit excellent optical quality and have resisted repeated cleaning and normal laboratory handling.

Creating a beam waist of the correct size at the entrance face of a fiber is the same as matching the cavity mode of a laser to that of the fiber. It requires knowledge of the diameter and curvature of the beam emitted by the laser, or equivalently, the size and location of the beam waist that would produce the beam. This information may be calculated from the cavity mirror curvatures and spacing or it may be determined by measurements on the beam. The focal length, image distance, and object distance of a lens to achieve the desired mode transformation may then be calculated.[8]

Calculations of this kind were made to match the mode of a Model 124 Spectra-Physics He-Ne laser into the HE_{11} distribution shown in Figure 2. A 10X microscope objective 150 cm from the front of the laser was predicted to give a good match. Both ends of a single-mode fiber were prepared in the manner illustrated in Figure 3, and the coupling efficiency, obtained with the lens at 150 cm, was found to be 0.7. The coupling efficiency was 0.63 or more with the lens within the range of distance between 120 cm and 170 cm. The measured efficiencies include the Fresnel reflection losses, so the mode-match efficiencies were slightly higher.

Effects of Temperature and Strain

The optical path length of a fiber is known to be sensitive to the temperature of the fiber and the pressure applied to it, as well as to longitudinal strain.[3,4] Longitudinal strain, as well as squeezing or twisting of the fiber, can be avoided by simple precautions. The effect of changes in atmospheric pressure have been shown to be negligible, pressure change of one atmosphere producing about one fringe per meter of length.[3] Temperature change of the fiber, therefore, is the primary extraneous cause of fringe shifts.

The mechanisms that bring about a change in the optical length of a single-mode fiber when its temperature changes are well understood. The effect is caused by a combination of the change in fiber length due to thermal expansion, and the change in propagation constant of the fiber as a result of changes in the index of refraction of the core and the cladding and the change in transverse dimension of the core. There may also be a strain-optic effect due to the difference in thermal expansion of the core and cladding. In general, however, the overall effect cannot be calculated with any precision because of lack of data on the materials used to make the fiber. For example, silica doped with germanium is frequently used as a core material, but the amount of the doping and its effect on the temperature coefficient of the index of refraction are difficult to find. For this reason, one must rely on experimental measurements of temperature effects.

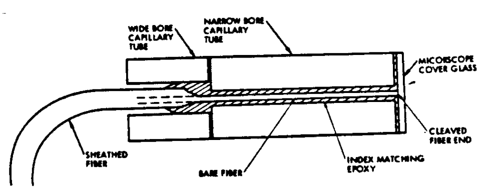

Figure 3. Method of preparing the ends of optical fibers to provide good optical quality, stripping of cladding modes, and ease of handling.

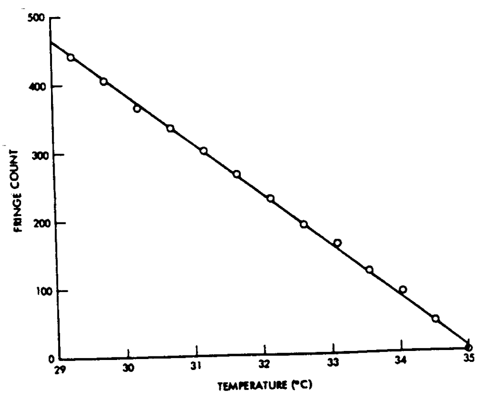

Figure 4. Change of optical length of a 1.75-meter length of Type T-110 optical fiber with temperature. The slope of the line is 44 fringes per °C per meter.

The change in optical length of a single-mode fiber was measured in two different experimental arrangements. In the first setup, the fiber was coiled and placed between two sheets of aluminum, using spacers to avoid compressing the fiber. A thermocouple was also placed between the metal sheets. The sheets were then wrapped in heating tape and enclosed in thermal insulation. In the second arrangement, the fiber was loosely wrapped around a 2-inch diameter copper rod, which also had a thermocouple and a heater attached. The rod was placed inside a Dewar, the mouth of which was closed with styrofoam. The capillary tubes on the ends of the fiber passed through the styrofoam in such a way that all of the exposed fiber was inside the Dewar flask. In both of these arrangements, the change in optical path length was determined by counting fringes over temperature changes of up to 20° C. Both sets of measurements were repeatable, and both arrangements gave the same results. One set of points is plotted in Figure 4. The slope of the line is 44 fringes per °C per meter.

The polarization transmitted by a single-mode fiber is also known to be affected by temperature and strain. Since control of polarization is essential to successful interferometry, measurements of these effects were made. Linearly polarized light was incident on one end of the fiber, and the light emerging from the other end was analyzed to determine its state of polarization. Birefringence effects could be easily observed whenever the fiber was bent, twisted, or squeezed. Birefringence effects due to thermal changes were also observed, and these were investigated in more detail. It was found that the polarization effects disappeared when all of the fiber was inside the isothermal enclosure. In other words, the polarization effects seem to be due to temperature gradients, rather than to changes in temperature. This result is not difficult to explain, since one would expect a fiber to be optically isotropic as long as it is at a uniform temperature. Detailed studies on the polarization effects can be found in references 9-11.

Applications of Single-Mode Fiber Interferometry

Fabry-Perot Etalon

Experiments were performed with a Fabry-Perot etalon made from a single-mode fiber held in a capillary tube in a way similar to that illustrated in Figure 3. The sheaths were first taken off of the fiber so that cladding modes could be removed, and the fiber was epoxied into the capillary tube. The ends of the fiber were then polished flat and parallel to each other, and 90% reflectance aluminum mirrors were evaporated onto the ends. Although metal mirrors of this type have appreciable absorption, the finesse of the etalon should not be effected by the absorption.

The etalon was tested with a multimode He-Ne laser by measuring the transmittance of the device as its length was changed by heating it. Figure 5 shows the intensity of the transmitted beam as the etalon was heated and cooled.

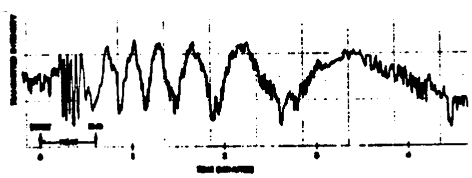

Figure 5. Transmitted power through a Fabry-Perot etalon made from a 5-cm length of single-mode optical fiber, as the device is heated and cooled.

The closely spaced fringes at the left occurred during the rapid heating and the widely spaced fringes represent the slower cooling of the device. The multimode character of the laser beam prevents the true finesse of the etalon from being observed, since the maximum and minimum transmittances occur at different times for different wavelengths.

Care will be required to construct an optical fiber etalon with high finesse because of the problem of getting good effective reflectivity of the mirrors. This difficulty arises because reflection of the optical wave at the end of the fiber is really equivalent to turning the wave around and re-injecting it into the fiber. The returning wave must be matched in phase to get good coupling, as discussed previously. If the end surface of the fiber is slightly tilted with respect to the axis of the fiber, the reflected wave does not match the field distribution of the mode, and the coupling is correspondingly reduced. A similar reduction in coupling would result from any gap between the end of the fiber and an external mirror. The radiation would emerge from the fiber and expand by diffraction. If the mirror were more than a few wavelengths from the end of the fiber, the expansion would be sufficient to introduce appreciable curvature in the wavefront and to reduce the coupling of the reflected wave back into the fiber. Any such effects directly reduce the effective reflectivity of the mirrors and the finesse of the etalon. Future etalons will be improved by using a capillary tube that fits the bare fiber more closely to avoid any tilt of the ends with respect to the axis of the fiber.

Unequal-Path Interferometer. An application of the capability of coiling up a long optical path into a small space is illustrated in Figure 6,

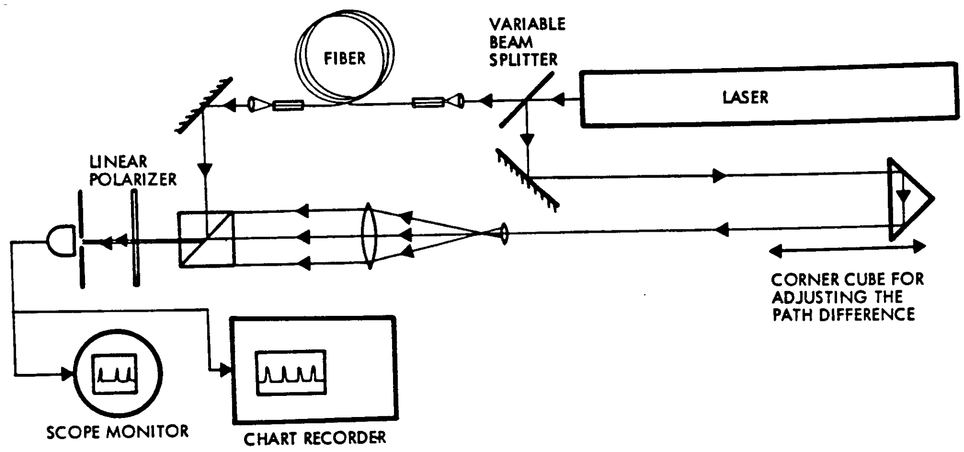

Figure 6. Unequal-path Mach-Zehnder interferometer method of measuring the frequency drift of a laser.

which shows Mach-Zehnder interferometer having a length of single-mode fiber in one of its branches. The other branch has a folded section with a corner-cube so that the difference in optical path length between the two branches may be conveniently adjusted to be an integral multiple of the length of the laser. In this way, temporal coherence between the two beams may be established and high contrast fringes may be obtained.

Since the two beams interfering at the detector traverse different path lengths from the laser to the last beamsplitter, they represent the radiation from the laser at different times. The order of interference between the two beams at any instant of time is equal to the product of the instantaneous frequency and the time delay, i.e.,

$$N = \nu\tau \qquad (5)$$

where N is the order of interference, ν is the frequency, and τ is the time delay between the two beams. The rate at which the fringes move is then

$$\frac{dN}{dt} = \nu \frac{d\tau}{dt} + \tau \frac{d\nu}{dt} \qquad (6)$$

If the time delay τ is constant and known, the rate of fringe shift is a direct indication of rate of frequency change. To the extent that the difference in optical path lengths can be kept constant, therefore, one is able to measure rate of change in the frequency of a laser by simply counting fringes. And since the difference in optical paths may be quite large, very small rates of frequency drift may be measured. For example, a 300 meter optical path length difference gives a transit time difference of 1 microsecond. One fringe per second then corresponds to a frequency drift of 1 MHz, which for a He-Ne laser, is less than one part in one hundred million.

To illustrate this technique, the optical arrangement of Figure 6 was set up to measure the frequency drift of a Spectra-Physics Model 124 He-Ne laser. A 128-meter length of single-mode optical fiber was placed in one branch to create the difference in optical path length, and a Hewlett-Packard Model 7702B strip chart recorder was used to record the interference fringes. Fringes were recorded at frequent intervals over a period of four hours after the laser was turned on. The rate of fringe shift as a function of time is plotted in Figure 7.

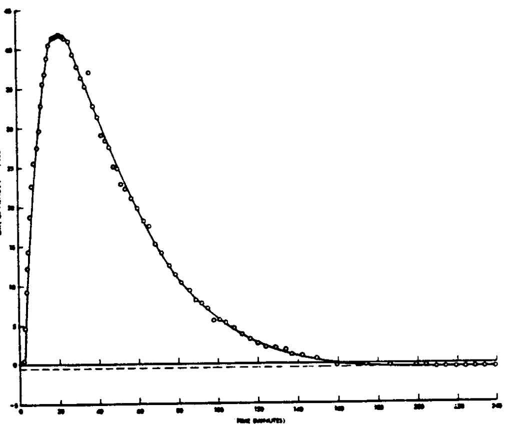

Figure 7. Rate of fringe shift in the unequal-path interferometer, showing the effect of the laser frequency drift and the correction for the temperature rise of the fiber. (See text)

It may be seen from this curve that the He-Ne laser has a highly variable rate of frequency drift during warmup. The peak rate, calculated from the difference in the optical lengths of the branches of the Mach-Zehnder interferometer, is 68 MHz per second. Since the intermode spacing of the laser is 214 MHz, and the line width is only 1.4 GHz, only six or seven longitudinal modes can exist at one time, the amount of frequency tuning shown in Figure 7 corresponds to a large number of modes passing through the gain profile rather than a single frequency being continuously tuned. As the laser continues to warm up and the temperature distribution of its parts approaches a steady state, the rate of frequency drift decreases monotonically.

As noted above in Equation 6, the rate of fringe shift may also be affected by changes in the time delay, or optical path length difference. For this reason, the coil of fiber was enclosed in thermal insulation during the measurements, and its temperature was monitored with a thermocouple, using an ice-water bath as a reference. The temperature of the fiber was observed to rise at a slow and nearly constant rate of 5×10^{-3} °C per minute for the duration of the measurements. For the 128-meter fiber, this rate of temperature rise, using the data of Figure 4, should produce half a fringe per second.

As a laser warms up, its optical cavity increases in length, so that each mode of the laser should drift toward lower frequencies. As the fiber gets warm, its optical length increases. The two terms on the right-hand side of Equation 6 thus have opposite signs in this case. The overall rate of fringe shift is dominated at first by the laser, but as the laser frequency stabilizes, the two effects become gradually closer in magnitude, until, at the point where the curve goes through zero, they exactly cancel. After a sufficiently long time, the drift of the laser becomes negligible and the curve becomes asymptotic to the dashed line representing the steady temperature drift of the fiber.

Although the overall frequency drift of the laser is well-behaved and repeatible, the rate does not change smoothly. The fringes sometime move rapidly and sometime slowly, occasionally stopping altogether. This variability is shown by the scatter of points about the curve.

Conclusions

It has been shown that the difficulties of coupling radiation into single-mode fibers can be overcome and that efficient coupling may be readily accomplished. Once the ends of the fibers are properly prepared, the fibers require no more care in handling than other optical components, and interferometers involving single-mode fibers may be set up with ease. The unique features of fibers are certain to lend themselves to a wide variety of new interferometric applications.

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References

1. V. Vali and R. W. Shorthill, Appl. Opt. 15, 1099-1100. 1976.
2. S. Lin and T. G. Giallorenzi, Appl. Opt. 18, 915-931. 1979.
3. G. B. Hocker, Appl. Opt. 18, 1445-1448. 1979.
4. J. A. Bucaro, H. D. Dardy and E. F. Carome, Appl. Opt. 16, 1761-1762. 1977.
5. J. AuYeung and A. Yariv, J. Opt. Soc. Am. 69, 803-807. 1979.
6. D. Marcuse, Light Transmission Optics, (Van Nostrand, New York). 1972.
7. Yu M. Popov and N. N. Shuikin, Sov. J. Quant. Electron, 4, 986-987. 1975.
8. R. J. Pressley, Handbook of Lasers, pgs. 421-441, (Chemical Rubber Co., Cleveland). 1971.
9. R. Ulrich and A. Simon, Appl. Opt. 18, 2241-2251. 1979.
10. R. Ulrich and M. Johnson, Opt. Lett. 4, 152-154. 1979.
11. M. Johnson, Appl. Opt. 18, 1288-1289. 1979.

Question (Howard E. Morrow, Lockheed Missiles and Space Co.): Is the input aperture of the fiber similar in behavior to a spatial filter in its beam "clean-up" behavior?

Answer: A single-mode fiber is a mode filter, the output of which is very similar to a pure gaussian beam. It is a better filter for this purpose than a pinhole spatial filter, which sharply truncates the beam passing through it, producing unwanted structure in the radiation pattern.

Question (Robert Yoder, Union Carbide Corp.): What differences in stiffness are involved in stripping away the plastic cladding for replacement by epoxy, and what was the motivation for doing so?

Answer: The motivation for surrounding the fiber with index-matching epoxy is to allow the radiation in the cladding modes to escape. If not removed, this radiation is superimposed on the output beam and interferes with it.