Splicing tolerances in graded-index fibers

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Calculations are presented showing that, in general, a parabolic-index fiber is more sensitive to lateral misalignments within a splice than a step-index fiber. However, misalignments result in the excitation of leaky modes in graded-index fibers, and this can lead to optimistic joint loss measurements. Effective losses are given for various lengths of fiber following the splice, and it is shown that a parabolic-index fiber may appear more tolerant to misalignment than a step-index fiber when short lengths are used.

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The achievement of a low-loss splice between two optical fibers requires a high degree of both lateral and angular alignment.[1] An imperfectly made joint fails to match the emitted radiation from one fiber to the acceptance cone of the other, and this results in a radiation loss. The magnitude of the loss depends on the degree of misalignment, the most likely imperfection in practice being a lateral displacement of the core centers. Such a misalignment also causes a redistribution of power amongst the fiber modes, and will excite higher-order modes which usually have a higher loss. Thus a spatial transient[2] follows a fiber splice as the steady-state modal distribution establishes itself, and the full effect of the splice on fiber loss will not be seen unless measurements are made a sufficient distance after the joint for the transient to have subsided.

A principal cause of such a spatial transient in graded-index fibers is the excitation of tunneling leaky rays. In step-index fibers, all leaky rays are found in an angular region outside the numerical aperture,[3] and therefore cannot be excited by a simple lateral displacement between the emitting and receiving fibers (assuming that only bound rays are present in the emitting fiber). This is not the case for a misalignment between two graded-index fibers, as it has been shown[4] that all leaky rays are contained within the meridionally defined numerical aperture, and therefore will be excited by even a small misalignment.

The purpose of the present letter is twofold. First, it is to calculate the losses produced by a laterally misaligned splice between two parabolic-index fibers, and to compare this with a splice between step-index fibers. It will be assumed that both emitting and receiving graded-index fibers are long, and therefore the spatial transients associated with the initial excitation and with the splice have subsided. A second objective is to calculate the leaky mode power loss within the transient region following the splice, and hence to determine the influence of the transient on the measurement of splice performance.

To simplify the calculation of splicing efficiency, we assume that (a) the emitting fiber is long and leaky modes are no longer present; (b) the remaining modes, i.e., the bound modes, are equally excited; (c) the fiber end faces are in contact; and (d) the only misalignment is transverse. Provided the fiber supports sufficient modes to allow a geometrical optics approximation, the problem then becomes one of calculating the overlap of the emitting fiber radiation cone with the local acceptance cone of the receiving fiber at a common point on their end faces, followed by a summation of this overlap over the common core area. For a step-index fiber the solution simply involves a calculation of the common area, since the local acceptance angle for bound modes is constant over the end face, and therefore leaky modes are not excited by a misalignment, as noted above.

For a graded-index fiber, however, the local acceptance angle varies with position on the fiber end face. This is illustrated schematically in Fig. 1(a), where we see that the local acceptance cone for leaky rays is always larger than that for bound rays, except at the core center. The equations defining the angular acceptance regions shown in the figure have been given in an earlier publication[4] in terms of the local angle of incidence. A plan view of a parabolic-index fiber is shown in Fig. 1(b), together with a superimposed section through the acceptance cones at a specific radius. From

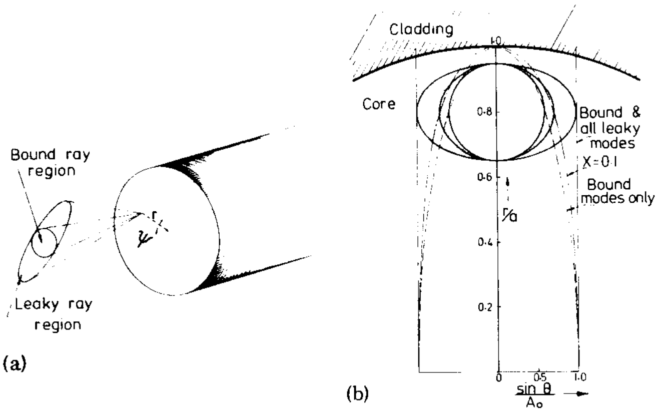

FIG. 1. (a) Schematic acceptance cones for rays incident on a parabolic-index fiber end face at radius r. The inner (circular) acceptance cone defines the acceptance region for bound rays, while the outer (elliptical) cone defines the region containing leaky plus bound rays. The shaded area, therefore, represents the angular region within which leaky rays are accepted at this radius. (b) Plan view of fiber end face shown in (a) with section through acceptance cones drawn at $r/a = 0.8$. As in (a) the shaded region between the circular and elliptical acceptance cones contains the leaky rays. The intermediate elliptical cone within the shaded region represents the effective acceptance angle, drawn in this case for $x = 0.1$ (see text). Also shown is the locus of the extrema of the bound ray acceptance cone (dashed lines), that of the bound plus leaky rays (vertical solid lines), and that of the effective acceptance cone (chain dotted).

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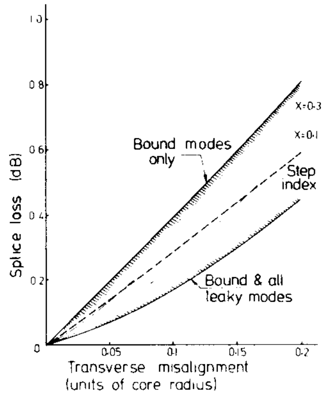

FIG. 2. Splice loss as a function of lateral fiber misalignment for a parabolic-index fiber. The shaded region represents an area of apparent splice loss; the observed loss depends on the length of fiber after the joint, and the fiber parameters. Specific examples are given for fibers having X values as shown (see text). The upper bound gives the splice loss seen after a length sufficient for the transient to have subsided. Shown for comparison is the loss calculated for a step-index fiber (dashed line). Note that this line and the upper and lower bounds to the shaded region are independent of fiber parameters.

the loci presented in the figure, it can be seen that whereas the circle delineating the guided ray acceptance angle decreases from a maximum at the core center to zero at the core/cladding interface, the major axis of the ellipse defining the acceptance of the leaky rays remains unchanged, and is equal to the maximum acceptance angle at the core center.

In a practical case, we are not interested in the limits of acceptance of all leaky rays, but only of those having low radiation losses and which therefore persist for considerable lengths. We note that the losses of leaky modes will vary from zero for the least leaky (at cutoff) to infinity for the most leaky (at the transition to radiation modes). Furthermore, we have previously shown[5] that this loss exhibits a rapid increase at some critical longitudinal propagation constant β (or, equivalently, angle of incidence Θ), thus dividing the low-loss from high-loss modes. This transition enables us to define an effective angular acceptance region on the end face; the exact dimensions of the region will depend strongly on the core radius a, wavelength λ, numerical aperture A_0, and length of fiber z from the point where leaky modes were first excited. A conic section defined in this way for a particular combination of fiber parameters is shown in Fig. 1(b), together with the locus of extrema of its major axis (the chain-dotted lines). The calculation of this new effective angular acceptance region is performed as follows.

The effective local numerical aperture $A(r,\phi,z)$ (sine of the effective local acceptance angle) is defined by summing the power injected at various angles of incidence Θ by a source having a Lambertian (cosine) distribution, suitably weighted by the attenuation coefficient $\alpha(\Theta,\phi)$:

$$A^2(r,\phi,z)=2\int_0^{\pi/2}\cos\Theta\sin\Theta\exp[-\alpha(\Theta,\phi)z/a]d\Theta. \quad (1)$$

The angle ϕ referred to here is the projected angle of a ray incident at radius r on the end face.[4] The values of the attenuation coefficient $\alpha(\Theta,\phi)$ vary from zero for the guided region to ∞ for the refracted region. In the intermediate (leaky) region the WKB approximation may be used to obtain expressions for $\alpha(\Theta,\phi)$.[5,6] For a parabolic-index fiber, treating only the least leaky rays, a useful approximation is[5]

$$\alpha(\Theta,\phi)=\frac{2}{n_2}\,\frac{r}{a}\,\sin\Theta\cos\phi\left\{\left[\left(\frac{\sin\Theta}{A_0}\right)^2-1+\left(\frac{r}{a}\right)^2\right]^{1/2}\right.$$
$$\left.\times\left[\left(\frac{2}{e}\right)\left(\frac{r}{a}\right)\frac{\sin\Theta}{A_0}\cos\phi\right]^{-1}\right\}^{\gamma}, \quad (2)$$

where $\gamma=2(r/a)v\cos\phi(\sin\Theta/A_0)$. Here A_0 is the meridional numerical aperture (defined at $r=0$), $v=aA_0 2\pi/\lambda$ is the normalized frequency, and n_2 is the cladding refractive index.

A simple expression for $A(r,\phi,z)$ may be obtained from Eq. (1) by introducing a linear approximation to the exponential term. This yields an effective upper limit to $\sin\Theta/A_0$ using Eq. (2), and renders the integral in (1) trivial. Additionally, when this linear approximation is performed, it is clear that the fiber parameters and length enter principally in the form $(1/v)\ln(z/a)$, suggesting the normalization parameter $X\equiv(1/v)\ln(z/a)$ used previously in calculations of near-field intensity distributions.[5,7] The intermediate acceptance cone of Fig. 1(b), as delineated by the effective local numerical aperture $A(r,\phi,z)$, was calculated for $X=0.1$.

We now apply the concept of effective local acceptance angle to the calculation of jointing efficiency $\eta(d,X)$ between two identical fibers having a lateral displacement d:

$$\eta(d,X)=\left\{\int_{S_E\cap S_R} r\,dr\,d\psi\int[A_R(r,\phi,z)\cap A_E(r,\phi,\infty)]^2\,d\phi\right\}$$
$$\times\left[\int_{S_E} r\,dr\,d\psi\int A_E^2(r,\phi,\infty)d\phi\right]^{-1}. \quad (3)$$

Here S_E and S_R are the core areas of the emitting and receiving fibers, respectively, and $S_E\cap S_R$ (a function of d) is the area of overlap; z is the length of fiber after the splice, and ψ is the angle associated with the radius r to the launch point [see Fig. 1(a)]. A_R and A_E are the effective local numerical apertures of the receiving and emitting fibers, defined by Eq. (1), and $A_R\cap A_E$ is the angular overlap. The use of $z=\infty$ in the denominator indicates that the emitting fiber is long and therefore only guided modes are present. The first integral in both the numerator and denominator of (3) refers to the geometry of the fiber end faces, while the second refers to the geometry of the angular acceptance and emittance cones.

The splicing efficiency between two identical parabolic-index fibers is shown in Fig. 2 as a function of lateral displacement, and may be compared with that between two step-index fibers. The shaded region represents results for a fiber length within the spatial transient regime, where the loss measurement will depend on the particular fiber parameters and the distance after the splice. The upper bound to the shaded region gives the loss when observations are made some distance after the splice, and no leaky modes are present. From this curve we see that the loss varies almost linearly with displacement over the range shown, and that under these conditions a parabolic-index fiber is more sensitive to misalignment than a step-index fiber, the loss for a given displacement being about 35% higher.[8] Typically, a 100-μm core diameter parabolic-index fiber requires alignment to better than 6.4 μm to achieve a loss of 0.5 dB, while an equivalent step-index fiber requires 8.6 μm.

The effect that the presence of leaky modes can have on a measurement may be illustrated by considering a splice made 2.5 m from the end of a fiber having a numerical aperture of 0.18 and a core diameter of 60 μm ($X = 0.3$ for $\lambda = 0.9$ μm). Referring to the figure, a parabolic-index fiber now appears slightly less sensitive to misalignment than a step-index fiber, at least up to a relative displacement of 0.06. Fibers having larger core diameters and numerical apertures exhibit the effect more strongly, and this clearly illustrates the pitfalls in measuring joint losses in short fiber lengths.

When both emitting and receiving fibers are long, so that leaky rays are no longer important, parabolic-index fibers are somewhat more sensitive to lateral misalignment than step-index fibers. A displacement tolerance of about 10% of the core radius must be achieved for acceptable splice performance (0.5 dB).

A spatial transient caused by the excitation of leaky modes follows an imperfect splice, and measurements made within this region will be optimistic. For example, a parabolic-index fiber may appear more tolerant to misalignment than a step-index fiber. Measurements made within the spatial transient may be extrapolated to longer lengths by use of the X parameter introduced here.

A further consequence of the transient following a splice is that a succession of closely spaced joints will not produce an additive loss.[1] Finally, it should be noted that the curves of Fig. 2 are not directly applicable to partially excited fibers, where a greater tolerance to misalignment is anticipated.

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