OPTICAL SCIENCES

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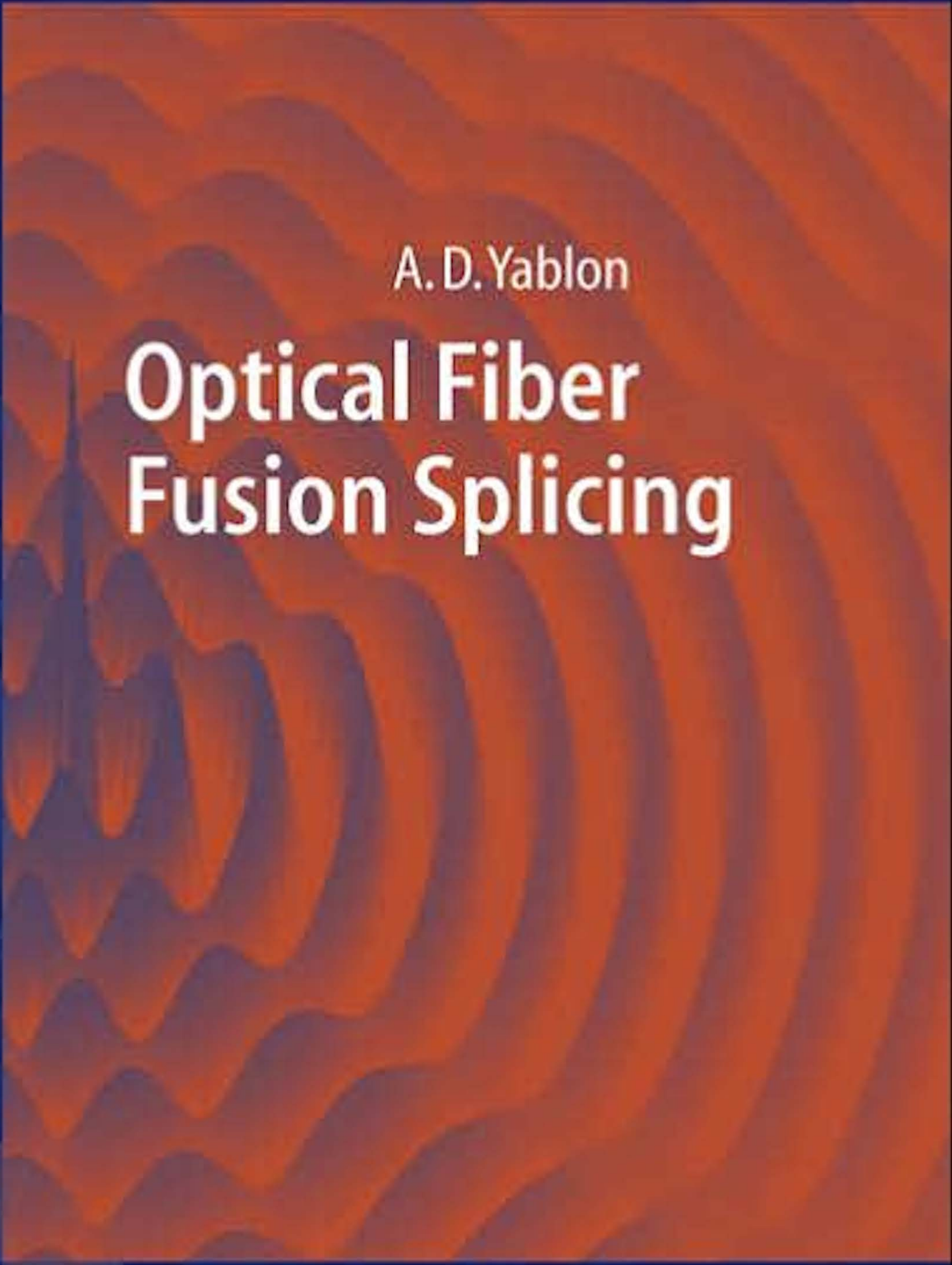
Optical Fiber Fusion Splicing



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necessary for measuring the reflectance of optical fiber fusion splices. Fig. 7.10 schematically depicts an OFDR containing a Michelson interferometer constructed using a chirped narrow-linewidth laser source. The chirp applied to the laser frequency ensures that optical interference between the reference and sample arms has a beat frequency that is proportional to the time delay between the signals returning from the sample and reference arms [7.17]. An OTDR-like trace indicating reflectivity as a function of distance can be generated from the Fourier transform of the detected signal. The spatial resolution of OFDR is on the order of 10 μm, which is about an order of magnitude inferior to OLCR, whereas the measurement range is about 10 m [7.17], which is substantially higher than OLCR. The minimum measurable reflectance of a coherent OFDR is on the order of -150 dB, which is comparable to OLCR.

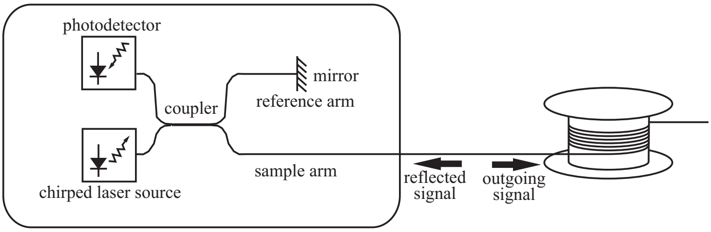

Fig. 7.10. Schematic illustration of a coherent OFDR in which a Michelson interferometer in combination with a linearly chirped laser source. After [7.17]

7.3 Refractive Index Profiling of Fibers and Fusion Splices

The optical characteristics of a fusion splice are entirely determined by the refractive index profile of the optical fibers in the vicinity of the splice. Consequently, understanding the refractive index profile of a fusion splice can be helpful during splice optimization of difficult fusion splices, such as those between dramatically dissimilar fiber types. Refractive index profiling is particularly useful for measuring and understanding transition splice loss, which was described in Sect. 4.2. When excessive fusion splice loss cannot be ascribed to core deformation, poor cleaves, or poorly optimized fusion splice parameters, refractive index profiling can be an effective diagnostic tool. However, refractive index profiling of fusion splices is a tedious and complex process that is not applicable to field or even factory fusion splicing, and is only practical in the laboratory.

In Sect. 4.4 we showed how the beam propagation method (BPM) can be used to numerically compute how an axial variation in refractive index profile affects a propagating signal. In Sect. 5.2 we showed how coupled-mode theory

(CMT) can be used to compute the effect of core deformation on fusion splice loss. In this section, we describe how to obtain measurements of the fiber's refractive index profile in the vicinity of the splice that can subsequently be used in conjunction with either CMT or BPM to estimate the optical characteristics of fusion splices.

Several different approaches for measuring the refractive index profile of optical fibers have been developed, including the refracted near field (RNF) [7.2, 7.9, 7.16], the transmitted near field (TNF) [7.2, 7.9, 7.16], the focusing method [7.2,7.9], and the transverse interferometric method (TIM) [7.2]. RNF is the dominant commercial approach for measuring the refractive index of optical fibers. However, both RNF and TNF are destructive measurements in the sense that they require access to a cleaved end of the optical fiber. Moreover, both RNF and TNF measurements average the refractive index over a length of several hundred microns in the vicinity of the cleave. This is a disadvantage when analyzing fusion splices where large variations in the fiber's refractive index profile occur within a few hundred microns of the fusion splice joint due to dopant diffusion (Sect. 3.3), viscous deformation (Sect. 3.2), or stress relaxation (Sect. 3.4).

Although they are not commercially available, the focusing method and TIM, are nevertheless attractive because they can non-destructively measure fiber index profiles in the immediate vicinity of a fusion splice. Individual measurements can be made on axial segments of fiber as thin as 50 microns, so axial variations in the refractive index profile due to dopant diffusion, viscous deformation, or stress relaxation can be measured in the vicinity of a splice. Refractive index profiles measured by TIM or the focusing method can be fed into CMT, BPM, or another numerical algorithm to predict the optical characteristics of a fusion splice. TIM is preferred due to its superior accuracy and so it will be detailed here.

TIM is accomplished with the aid of an interferometer that measures the optical path length difference experienced by light rays traversing an optical fiber (Fig. 7.11a). Probe light is divided by a beam splitter into two beams, one of which passes transversely across the fiber, which is immersed in index matching oil to minimize refraction, while the other beam passes through an empty bath of identical index matching oil. A beam splitter recombines these two beams into a single beam that is imaged onto a CCD camera yielding an interferogram. By adjusting the optical elements in the interferometer, the light and dark bands, termed *interference fringes*, can be made to run transversely across the image of the fiber as shown in Fig. 7.11b.

The relative shifts in the bright and dark bands of the interferogram are detected by a computer and can be directly related to the optical path length. A computer implementing the Abel integral transform reconstructs the fiber's refractive index profile from the detected fringe shifts. Details concerning the algorithm relating the fringe shifts to the fiber index profile are described in [7.2]. Note that because of a typo, the final plus sign in equation (4.5-25) of [7.2] should in fact be a minus sign.

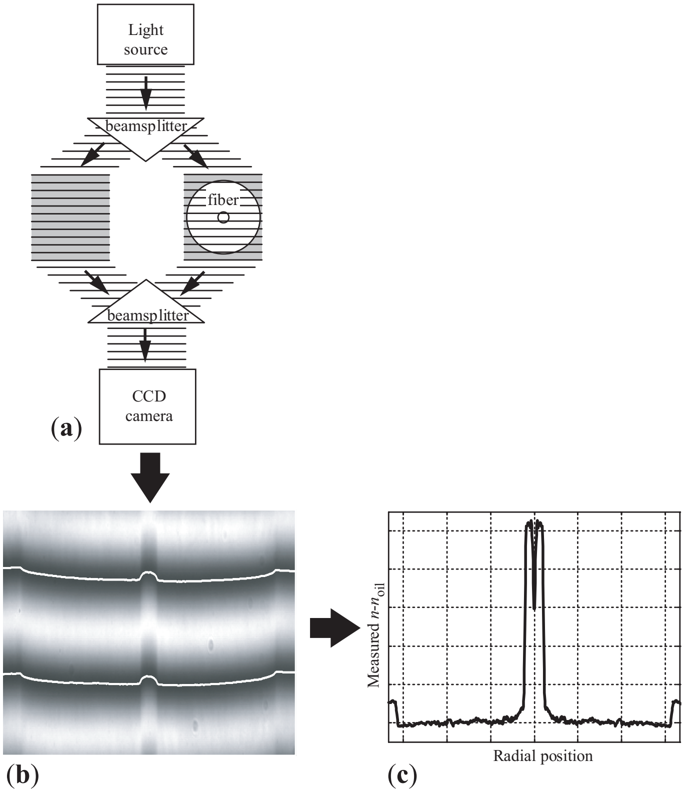

Fig. 7.11. Schematic illustration of refractive index profiling using the TIM method. The shading in each arm of the Mach-Zehnder interferometer depicted in (**a**) shows the location of refractive index matching oil. The parallel lines indicate the phase fronts of the probing light while the arrows indicate light propagation direction. In the interferogram, (**b**), heavy white lines overlaid on the dark fringes indicate computer-detected fringe positions. The shift in the detected fringe positions can be related to the optical path length, which is converted into the refractive index profile depicted in (**c**)

By axially translating an optical fiber fusion splice across the field of view of the interferometer, the refractive index profile can be measured as a function of distance from the fusion splice. In this way, axial variations in a fiber's index profile can be nondestructively measured and combined with numerical techniques such as BPM or CMT to estimate splice loss and mode coupling effects.

The algorithm described in [7.2] to extract the refractive index profile from the interferogram assumes that the light rays traversing the fiber are not refracted by the relatively small refractive index differences encountered as they traverse the fiber. In reality, some refraction does occur and this reduces the accuracy of the measurement. TIM is not effective for microstructured optical fibers described in Sect. 9.5 because the large refractive index difference between the glass and the voids causes too much refraction. The algorithm described in [7.2] assumes that the fiber is axisymmetric, so radial asymmetries will also reduce the accuracy of the index profile. For this reason, TIM is not effective for polarization-maintaining (PM) optical fibers described in Sect. 9.2.

7.4 Summary

Fusion splice loss is usually the most important optical performance characteristic of a fusion splice. It can be measured using transmission or reflection measurements. The choice of measurement technology depends on whether the fusion splice is analyzed in a research laboratory, in a factory environment, or during field installation of optical fibers.

The insertion loss or cutback techniques can be used to accurately measure fusion splice loss. The "pre-splice" approach yields accurate splice loss measurements even when the attenuation in the fibers themselves is significant yet unknown, or when distinct power meters must be used because the end of the fiber span is situated far from the fusion splice. The two-splice approach can eliminate measurement inaccuracies associated with reconnecting optical fibers to a source or detector. The wavelength dependence of splice loss can be measured with a broadband source and a wavelength sensitive detector or alternatively with a wavelength tunable source and a broadband detector.

Optical time-domain reflectometers (OTDRs) are indispensable for measuring single-mode or multimode fusion splice loss in optical fiber transmission cables either before or after installation. The apparent single-mode splice loss measured by an OTDR can sensitively depend upon the relative size of the fibers' mode field diameters (MFD) and so accurate splice loss measurement between dissimilar fibers usually requires that they be measured by the OTDR in both propagating directions. OTDRs are not effective at discriminating the individual loss contributions of closely spaced splices or components.

Although low-temperature fusion splices between dissimilar fibers can exhibit relatively high values of reflectance, the reflectance of most other fusion splices is well below the measurement limit of OTDRs or optical continuous wave reflectometers (OCWRs), which is on the order of -70 dB. More sophisticated devices, such as optical low-coherence reflectometers (OLCR) or coherent optical frequency-domain reflectometers (OFDR) can be used to measure fusion splice reflectance down to about -150 dB with sub-mm spatial resolution.

Refractive index profiling of a fusion splice using the transverse interferometric method (TIM) can be a powerful tool for splice optimization and for understanding otherwise unexplained splice loss, especially when combined with a numerical method such as coupled-mode theory (CMT) or the beam propagation method (BPM).