

Explanation of the Sources of Variation in Optical Fiber Effective Group Index of Refraction Values

AN4091

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Scope

This application note defines and differentiates index of refraction (IOR) from the effective group index of refraction (EIOR), explains the importance of EIOR values for optical time domain reflectometer (OTDR) measurements, and explains sources of variation in EIOR values.

The Basics: IOR vs. EIOR

The IOR is a material property that defines the speed of light in a specific medium. It is expressed as a ratio of the speed of light in a vacuum to the speed of light in the medium of interest:

$$n_{\text{material}} = \frac{c}{v_{\text{material}}}$$

In optical fiber, dopants are added to the core and sometimes the clad region to modify the IOR. The resulting refractive index difference between the core and cladding regions confines the light signal within the core through total internal reflection (a specific condition of Snell's Law). In single-mode fiber, a vast majority of the light signal travels in the core while a small amount of light travels outside the core/clad interface (or in the cladding). Thus, the light signal encounters the different indices of refraction of the core and the cladding depending on a specific fiber's profile design and operating wavelength. In multimode fiber, light encounters the varying refractive index values associated with the graded refractive index profile design that is common for communications grade fibers. The EIOR is a weighted average of all the indices of refraction encountered by light as it travels within the fiber. Therefore, EIOR represents the actual behavior of light within a given fiber.

The IOR is helpful in both system modeling and physical assembly situations. For example, one would need to know the IOR when identifying an index matching gel or designing a connector. The IOR can also be used to understand the power coupling when designing an optical component. In these situations, the user is seeking to minimize back reflections or loss at a localized joining point.

The EIOR is required for all optical measurements-based length and distance calculations; thus making it a critical fiber attribute for cable manufacturers. Cable manufacturers use the EIOR as part of OTDR measurements to verify fiber length prior to and after cabling and to isolate breaks in an installed fiber system. To help ensure agreement in fiber measurements, all parties involved should use the same EIOR values, which are supplied by Corning upon request.

Why is the EIOR Value Critical to Ensuring Good OTDR Measurements?

An OTDR works by sending a timed light pulse down the fiber and detecting light which is reflected backward (backscattered) as the forward propagating pulse of light travels along the fiber being measured. The OTDR detector captures information on the magnitude of the reflected light and time delay in order to report attenuation, length and position of other features in the fiber. The time delay can be converted into distance using the group velocity with which the light travels within the fiber. The EIOR, as a surrogate for the speed of light in the glass, is programmed into the OTDR to allow conversion of units from time to distance.

The logo for Corning, featuring the word "CORNING" in white, uppercase, sans-serif font centered on a solid blue rectangular background.

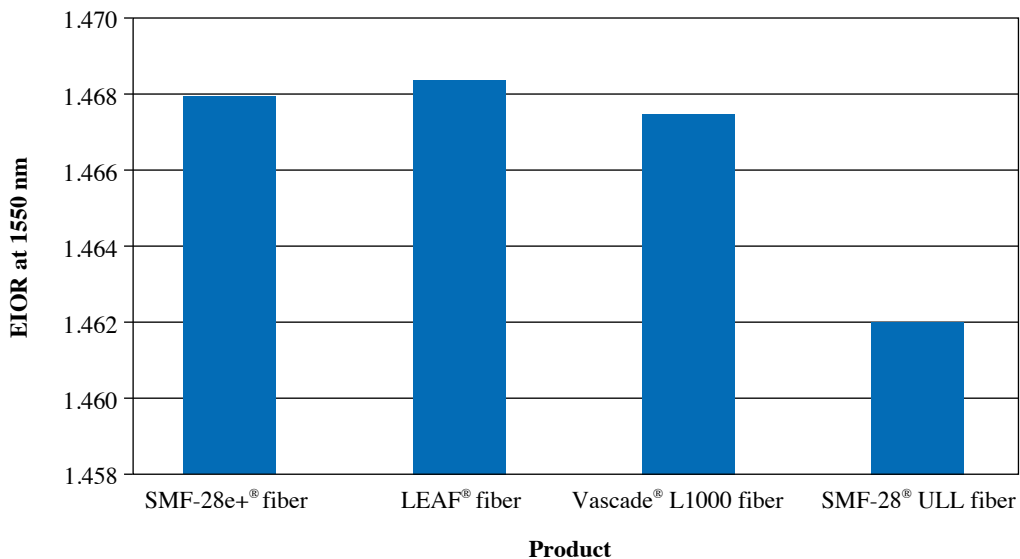
Sources of Variation in the EIOR Value

Source of Variation: Center Wavelength

Fiber suppliers like Corning quote EIOR at several reference wavelengths. However fiber is often used at different wavelengths. The EIOR will be slightly different at these wavelengths for two reasons: refractive index of a medium is a function of wavelength; and in optical fiber the mode-field diameter changes with wavelength which changes the percentage of power carried in the cladding region of the fiber. Thus, the EIOR is dependent on the nominal or center wavelength of the light source. When the difference between the center wavelength of the light source and the wavelength at which EIOR is defined is small (less than ~50 nm) these variations in EIOR are considered measurement noise and may be neglected. Above this threshold, variations in the EIOR values due to a bias between the center wavelength of field equipment and the wavelength at which EIOR is defined can become appreciable and have the potential of impacting length measurements. If you are uncertain of whether the EIOR being used in field equipment is correct at the wavelength of interest please contact Corning to obtain the appropriate EIOR value for a given wavelength.

Sources of Variation in the EIOR Value

The EIOR of an optical fiber will vary with the refractive index profile. The refractive index profile determines how light is guided within the fiber by defining the shape and size of the light carrying region. Profile shape is achieved by varying the level of dopants in the fiber core which alters the material composition of the glass and the local IOR. The figure below illustrates the impact of profile shape on EIOR by comparing EIOR values for several single-mode products with different refractive index profiles.

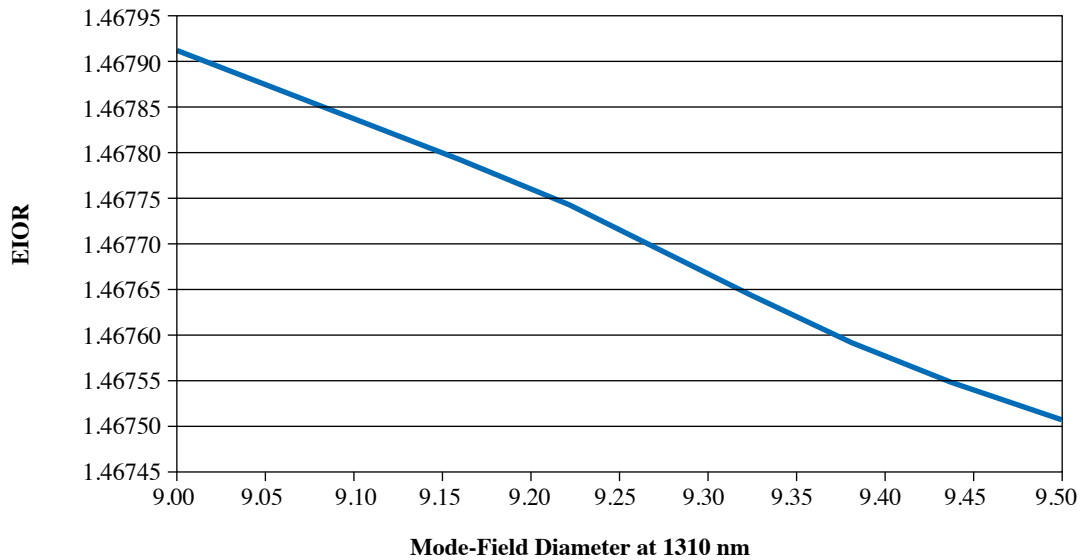


Impact of Profile Design on Various Single-mode Fiber Types

Figure 1

Figure 1: A comparison of the EIOR values for various single-mode fibers illustrates the impact of the refractive index profile. Each product in the graph above has a different profile shape and nominal MFD. In addition, Corning[®] SMF-28[®] ULL fiber has a lower EIOR because it has a silica core with no germania which is commonly used to increase the refractive index. Please note that the EIOR values in the above figure are for each product's nominal mode-field diameter.

The size of a fiber's light carrying region is represented by mode-field diameter (MFD) for single-mode fiber products and core diameter for multimode fibers. Changes to the size of the light carrying region can impact the EIOR value. Using the MFD as a surrogate for profile size, figure 2 illustrates the relationship between EIOR and MFD.



Impact of Mode-Field Diameter on EIOR for SMF-28e+® Fiber

Figure 2

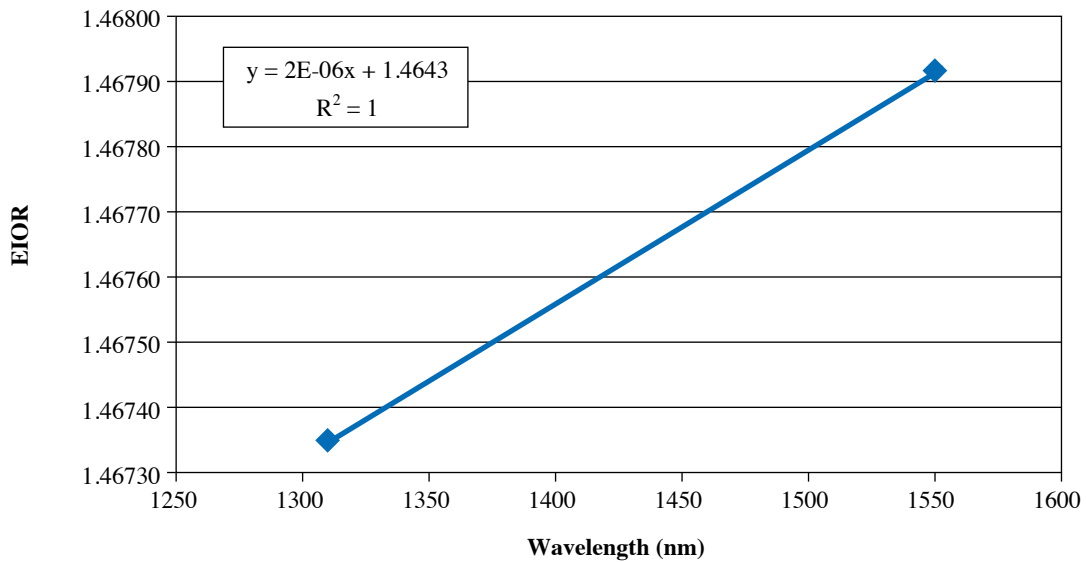
Figure 2: A comparison of EIOR values at various mode-field diameters illustrates how EIOR changes with core size in a particular product.

Source of Variation: Launch Condition (Multimode Fibers)

For multimode fiber with a graded refractive index profile, the EIOR is highly influenced by the launch condition. The launch condition directly determines the location of modes that are excited within the fiber. If the launch condition excites modes which are centered in the core of the fiber, the EIOR will be higher than that of a launch which excites modes on the periphery of the core. Therefore, the EIOR of a fiber measured with an overfilled light source will be different than when the fiber is used with a restricted mode launch.

What is the Best Way to Approximate EIOR Values at Non-Standard Wavelengths?

The rate of EIOR change with wavelength is neither monotonic nor linear. However, in the absence of empirical data, the best way to approximate the EIOR at a non-common wavelength is through linear interpolation. Within the limited spectral range of interest (i.e. a few hundred nanometers) a linear interpolation will produce acceptable values (± 0.0002). For single-mode fiber, this equates to an error of ~ 8 m on a 50 km length of fiber.



Linear Regression for SMF-28e+® Fiber

Figure 3

Figure 3: Illustrates linear regression between EIOR values at two wavelengths. This technique can be used to estimate EIOR values at non-common wavelengths. Please note that the EIOR values used in this plot are representative of Corning® SMF-28e+® fibers with a nominal mode-field diameter of 9.2 μm.

As noted in this applications note, there are several sources of variation in the EIOR value. Of the sources listed here, a change to the center wavelength is the single greatest source of length variation for single-mode fibers. To get the most accurate EIOR value, always ask Corning Optical Fiber for the typical value at the wavelength of interest.

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