MODE FIELD DIAMETER AND EFFECTIVE AREA MEASUREMENT OF DISPERSION COMPENSATION OPTICAL DEVICES

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ABSTRACT

In the fiber plant today there are many optical elements that pave the way for dense wavelength division multiplexing (DWDM) installation. The single-mode optical fiber deployed in most fiber plants is non-zero dispersion shifted at 1310 nm. Matching mode-field diameter (MFD) and effective area (A_{eff}) at DWDM light wavelength assures good transfer of light energy. For example, one current method of manufacturing a dispersion compensation element reduces the MFD and A_{eff} by 75-80%. This reduction significantly limits these elements to the ”gain-block” portion of the fiber plant. This is objectionable to service providers since they would like to place the dispersion compensation elements where needed and not just where the active elements, such as gain-block, are located. The problem is further compounded by additional functions, such as add/drop multiplexers, filters, isolators, etc. that many telecommunication equipment suppliers fit into each active area of the fiber plant. The importance of MFD and A_{eff} as a function of wavelength is also evident as the DWDM frequencies cover the “C” and “L” bands of EDFAs. When the “S” band becomes economically feasible, MFD and A_{eff} from 1380 to 1650 nm should be measured, particularly in the newer fiber which has the water peak suppressed.

This paper will discuss a quick and accurate measurement technique for MFD and A_{eff} using the far-field method based upon TIA/EIA test procedures FOTP 191 [1] and FOTP 132 [2], which call out this method as the reference for other measurement techniques. Refractive index profile (RIP) can be calculated as well using the biased perturbation method [3]. The measurement method uses a high speed scanning goniometric radiometer to obtain the far-field profiles over an angular extent of ±90° with greater than 60 dB dynamic range in less than 20 seconds. This measurement technique will allow service providers and their suppliers to rapidly and accurately measure the MFD and A_{eff}, enabling them to determine the capability of DWDM deployments. Careful attention to installation and testing of optical elements is essential to achieve maximum transfer of optical energy in the fiber plant maintained by telecommunication service providers.

INTRODUCTION

Dispersion management is one of the key attributes of optical fiber, which is necessary for successful deployment of DWDM. As channel density increases in number and decreases in spacing, dispersion has a greater influence in the ability to provide point-to-point communication. There are two types of dispersion: chromatic and polarization. Some chromatic dispersion is desirable since it aids in the suppression of undesirable four-wave mixing of DWDM wavelengths. There is considerable dispersion-shifted fiber optic deployed in the fiber plant. A typical fiber will have zero dispersion at 1310 nm, yet the major wavelengths are above 1500 nm in the “C” and “L” erbium bands. The dispersion characteristic of fiber must be managed by using components that have the inverse dispersion properties. Many of these components are generated with reduced MFD and A_{eff}, which limit location and effectiveness.

MFD and A_{eff} are two parameters which are used to describe the ability of optical fiber and other optical elements used in telecommunication to carry the information in various wavelengths of light contained in DWDM systems. In effect, these are defined by standards organizations as a method to specify various vendors' products used by telecommunication service providers and their equipment suppliers. Over the years, several test methods have been proposed and used to aid the service providers and equipment suppliers to understand the limits of optical elements deployed in the fiber plant. The technique used in this article is the direct far-field method using a goniometric radiometer apparatus, which is the reference measurement method used by standards organizations [1, 2]. The equation below represents the loss associated with MFD mismatch. As an example, an uncertainty in MFD of a typical single-mode fiber of 10% leads to a loss uncertainty of ~0.0394 dB, or ~0.9%. On the other hand, uncertainty of 0.5% leads to a loss uncertainty of ~0.00011 dB, or ~0.0025%.

$$\text{Loss}\,[\text{dB}] = -10 \cdot \log \frac{4}{\left(\frac{\text{MFD}_1}{\text{MFD}_2} + \frac{\text{MFD}_2}{\text{MFD}_1} \right)^2}$$

A discussion of A_{eff} can be considered here. The contribution of the nonlinear effects to transmission is defined as the power density (power/A_{eff}) times the length of the fiber. The A_{eff} is defined as the cross-section of the light path in a fiber. Depending on the type of fiber, the A_{eff} typically varies between 50 and 72 square microns, the lowest corresponding to dispersion-shifted single-mode fiber and the highest to standard single-mode fiber. The higher the optical power density and the longer the fiber, the greater the nonlinear contributions [5]. We are aware of some thermal expanded core fiber, with A_{eff} reaching several hundred square microns for a short distance in order to overcome the loss associated with physical mismatch.

There are several companies manufacturing dispersion devices. Each company should supply MFD and A_{eff} specifications as a function of wavelength to their customers. This will aid the deployment of these components. Using the goniometric radiometer technique, both fast and accurate measurements can be made. Where other methods may take hours, this method takes less than 20 seconds.

PRINCIPLE OF OPERATION

An instrumentation system was constructed based on the measurement technique. The principle of operation of the system is as follows: The end of the optical fiber under test is positioned at the axis of rotation of an optical fiber collector. The plane of rotation of the optical fiber collector is the far-field measurement plane. For typical single-mode and dispersion-shifted fibers operating at the wavelengths of interest, the far field is fully developed at a distance on the order of 1 mm, so the scan radius must exceed this value. For the system described here, the scan radius was greater than 6 cm, well into the far field, and the data is acquired over an angular range of ±90°. The collected light then propagates to a stationary InGaAs detector. The detector signal is amplified by a transimpedance amplifier followed by a voltage amplifier with a total programmable gain range of 140 dB.

The measurement system is automated using a PC-based scan control and data acquisition system. An optical encoder on the rotating fiber collector and a phase-lock circuit provide motion control feedback and precise angular sampling. Here, the data was acquired with an angular sampling resolution of 0.055º. The scan rate was 10 Hz, so single far-field scans are acquired every 50 ms.

The amplified signal is input to the PC-based data acquisition system, where the profile data from each scan are digitized and stored in computer memory. To obtain far-field profiles with the high dynamic range required to accurately measure MFD and A_{eff}, (>50 dB) multiple high-speed scans are acquired at different incremental gain settings. The data from these multiple scans, each acquired with dynamic range of 24 dB, are then reassembled to provide the far-field profile with dynamic range typically greater than 60 dB. This dynamic range is comparable to that obtained using conventional lock-in amplifier techniques, but here the profiles are acquired at much higher speed. In the present system the gain ranging method allows far-field profiles to be obtained with dynamic range of 64 dB for a single-mode fiber source operating at a power level of 0 dBm (1 mW). For a 30 dBm (1 Watt) fiber source, the obtainable dynamic range is 94 dB.

The far-field data acquired is used primarily to determine the MFD and A_{eff}, of single-mode and dispersion-shifted fibers. These parameters are measured in accordance with the Telecommunication Industry Association/Electronic Industries Association (TIA/EIA) standard using the Direct Far-Field (DFF) method described in the Fiber Optic Test Procedures (FOTP's). Specifically, the MFD is calculated using the DFF method and the Petermann II integral as per FOTP-191, and A_{eff} is determined with the DFF method as given in FOTP-132. Other parameters of interest are angular widths and Numerical Aperture (NA) [4] at different levels, amplitudes at specified angles, peak and centroid angular positions, 3D centroid, total integrated relative power and power in selected cone angles.

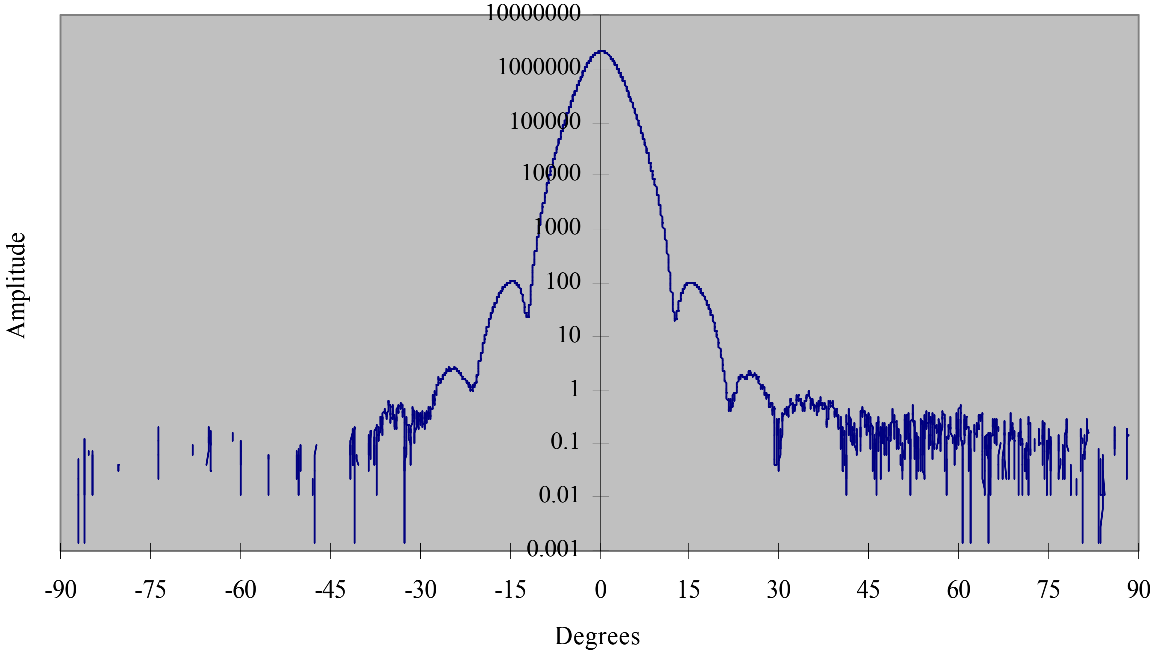
With this method, the far-field profile is acquired and the corresponding MFD and A_{eff} parameters are reported in less than 20 seconds. The NA and other parameters can be reported in real-time. The measurement accuracy for MFD is ±0.5%, and for A_{eff} and NA it is ±1%. A graphical user interface facilitates system operation and the display of raw profile data and the computed values for MFD and A_{eff}.

The scanning goniometric radiometer technique lends itself to the design of compact instruments suitable for portable field use. The scanning apparatus fabricated here has dimensions of 6.5 in. × 6.5 in. × 8 in. (16.5 cm × 16.5 cm × 20.3 cm).

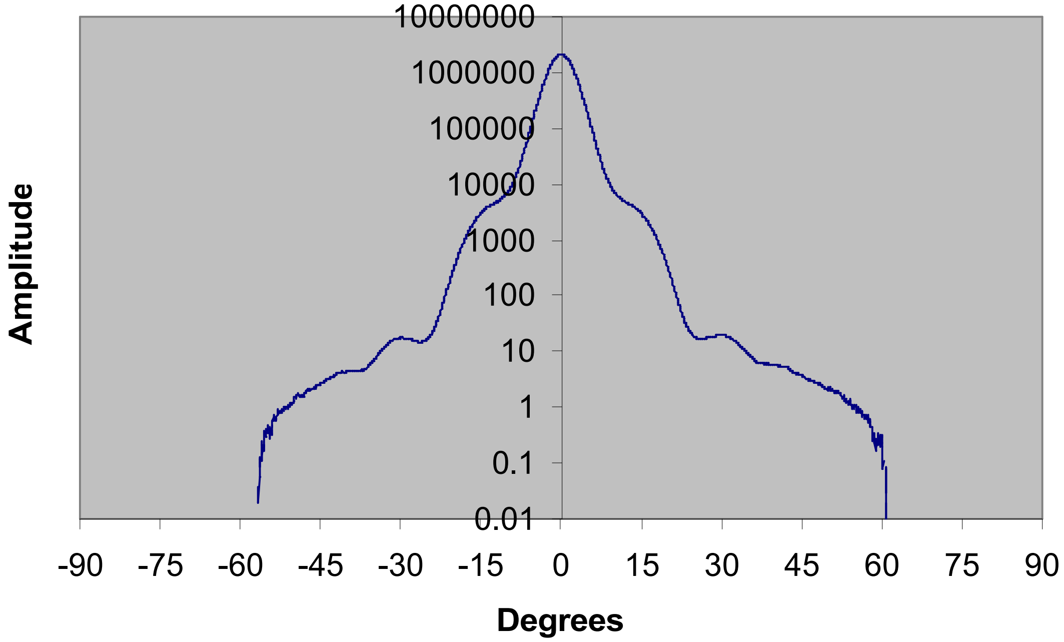
Finally, it is possible to obtain full 3-dimensional mappings of the far-field irradiance distribution of optical fibers by rotating the fiber under test about the measurement optical axis. This technique is useful for characterizing elliptical core fiber and also the uniformity of circular core fibers.

MEASUREMENT EXAMPLES

A typical far-field profile obtained for a sample single-mode fiber is shown in Figure 1a, and for a dispersion-shifted fiber in Figure 1b. Each profile was obtained in under 20 seconds. The measurement was made using a Fabry-Perot laser diode source operating at a nominal wavelength of 1300 nm and output power of 3 dBm (2 mW). The data here was transferred to a spreadsheet program for graphing. The data shows the complete scan range from -90° to +90° with signal amplitude ranging over 9 decades. In the single-mode fiber profile, two sets of cusps are clearly defined, and two more cusps can be seen where the signal approaches the background noise level at the 0.1 amplitude level. For accurate MFD and A_{eff} calculation, the angular extent of the measurement must be large enough to include the tails of the distribution, especially true for dispersion-shifted fibers which have a "wider" profile than typical single-mode fiber. This requirement is clearly met in the present system.



a) Single-Mode Fiber



b) Dispersion-Shifted Fiber

Figure 1. Far-field profile of a single-mode optical fiber (a) and dispersion-shifted optical fiber (b) obtained with the new scanning goniometric radiometer technique.

Measurements were performed to assess the “push-button” repeatability of the instrument. Table 1 summarizes the results for 3 different series of measurements of MFD and A_{eff}. The results for series “A”, with 250 measurements, had a 3σ repeatability of 0.004 μm for MFD and 0.463 μm^2 for A_{eff}. Similarly, the series “B” measurement had a 3σ repeatability of 0.0054 μm for MFD and 0.485 μm^2 for A_{eff}, and for series ‘C’ the values are 0.0095 μm for MFD and 0.512 μm^2 for A_{eff}.

Table 1. Mode-Field Diameter and Effective Area “Push-Button” Repeatability for 3 Series of Measurements

Series (# of measurements)	**A (250)**		**B (250)**		**C (1000)**	
Parameter	**MFD [μm]**	**A_{eff} [μm^2]**	**MFD [μm]**	**A_{eff} [μm^2]**	**MFD [μm]**	**A_{eff} [μm^2]**
Minimum	9.3886	69.603	9.3860	69.444	9.4367	69.736
Maximum	9.3954	70.099	9.3953	70.035	9.4588	71.384
Mean	9.3920	69.770	9.4588	69.727	9.4463	71.013
3 ´ Standard Deviation	0.0040	0.463	0.0054	0.4846	0.0095	0.512

The results show the 3σ push-button repeatability of the instrument is better than 0.01 μm for MFD and approximately 0.5 μm^2 for A_{eff}. These values are of the same order of uncertainty due alone to problems associated with the computation algorithms for MFD and A_{eff}. Some of the variation in parameter values is also attributed to fluctuations in the source amplitude and wavelength during the measurement, as evidenced by the broader range of MFD and A_{eff} values for the longer series “C” measurements. Finally based on numerous series of measurements, the overall accuracy of the instrument is conservatively specified at ±0.5% for MFD and approximately ±1% for A_{eff}.

The measurement of Numerical Aperture (NA) is measured in accord with the TIA/EIA Standard using the Far-Field Method described in FOTP-177 [4]. Specifically, the NA is obtained from the sine of the 5% intensity half angle. Angular width measurements are obtained with a standard deviation of approximately 0.05°, which gives a 3σ variation of approximately ±0.001 in the NA value for typical single-mode optical fibers, which is better than ±1%.

A preliminary series of measurements were performed to obtain MFD as a function of wavelength over the wavelength range extending from 1513 to 1593 nm. To obtain good statistics 250 measurements were performed at each wavelength. The results of these measurements are plotted in Figure 2. The graph shows the extreme maximum and minimum values for each data set and the average value. Clearly, the MFD for this fiber has a linear trend with wavelength, with slight deviations at 1558 nm and 1588 nm. (These may be due to systematic errors.) To highlight the speed of measurement, this data, representing over 4,250 measurements, was acquired over a period of 2 days. Using a conventional far-field scanning system that takes 30 minutes per scan, the same measurement would take approximately 265 man-days.

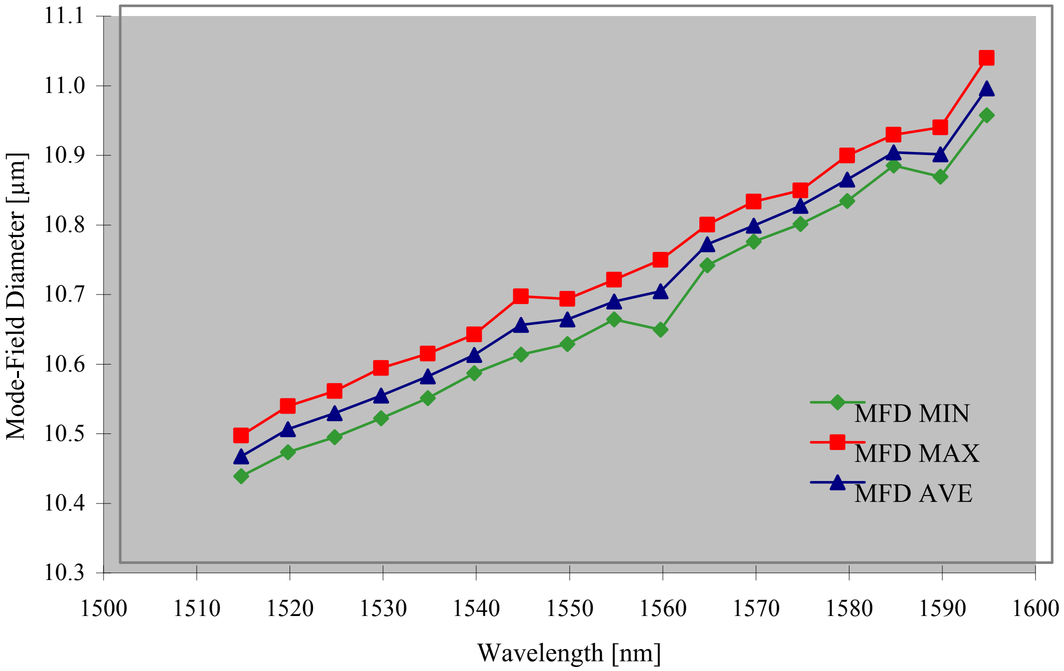


Figure 2. Preliminary results of a series of measurements to determine the variation of MFD with Wavelength. The data summarizes 250 measurements at each wavelength.

An example of a 3-dimensional measurement of the entire far-field of a single-mode-fiber is shown in Figure 3. This graphic was generated from data acquired from 50 scans made through different azimuth angles about the fiber axis by incrementally rotating the fiber in steps of 3.6°. The scale in the display is logarithmic. Two cusps in the field are readily apparent, as well as the symmetry of the distribution. This measurement took approximately 17 minutes to complete.

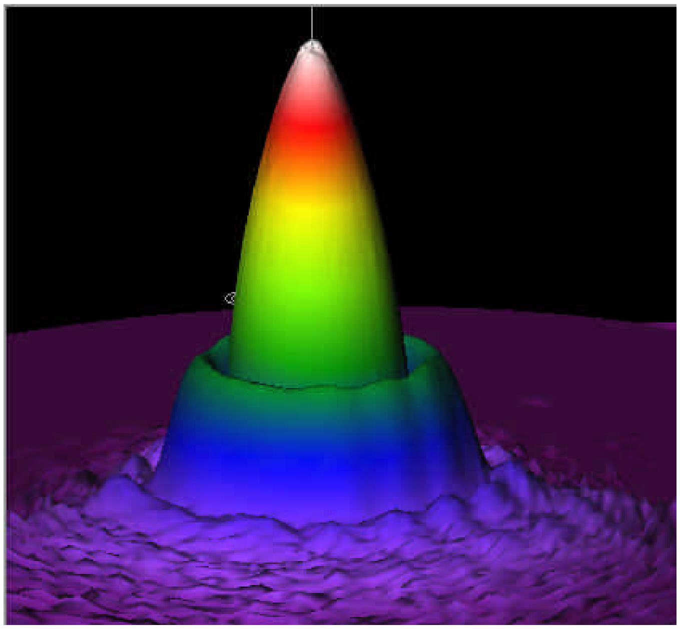


Figure 3. Example of 3D representation of far-field irradiance of a single-mode-fiber.

CONCLUSION

We have shown that the goniometric radiometer measurement technique can rapidly provide far-field profiles with the high dynamic range and extent of angular scan required to accurately measure MFD and A_{eff} of single-mode and dispersion-shifted optical fibers. The speed and accuracy of the measurement makes it possible to test greater numbers of fibers both reliably and economically. This method also allows many measurements to verify the wavelength dependence of optical elements in the fiber plant. This becomes more important as the complexity of the fiber plant increases due to the deployment of DWDM. The technique also lends itself to the design of compact instruments suitable for portable field use. This may prove useful in the deployment and repair of fibers where the loss budget is critical.

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