

Single Spectrum Cutoff Wavelength Measurement Method for Multicore Fibers

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Abstract: We propose a simplified cutoff wavelength measurement method for multicore fibers, which derives an upper bound on the maximum cutoff wavelength among the cores from a single spectral attenuation measurement employing full-mode, full-core excitation. © 2025 The Author(s)

1. Introduction

Space division multiplexing (SDM) is a promising technology for increasing the transmission capacity of optical networks [1]. Multicore fiber (MCF) has been recently commercialized for submarine applications [2], and there is a drive for yet broader adoption across diverse applications, including terrestrial uses. To facilitate this transition, it is crucial to improve the productivity of MCF manufacturing. This improvement should encompass not only the production process but also the efficiency and throughput of post-production inspections.

One approach to enhancing the efficiency and throughput of MCF inspections is the simultaneous measurement of the optical properties of all cores. Although parallel measurement of individual cores using fan-in/fan-out (FIFO) devices and duplicate measurement setups is possible, this scheme requires significant investment in measurement instruments. Therefore, simplified measurement methods that enable simultaneous measurement at reduced cost are desired, even if it requires sacrificing the ability to distinguish the characteristics of individual cores. A good candidate for applying such methods is the cutoff wavelength (λ_c) measurement, as it is sufficient to ensure single-mode operation if the maximum λ_c ($\lambda_{c,\max}$) among all cores is shorter than the minimum operating wavelength. Ohashi *et al.* have previously proposed a simplified λ_c measurement method where all modes of all cores are excited and received [3,4]. This method can “estimate” $\lambda_{c,\max}$ [3,4]; however, in principle, the true value of $\lambda_{c,\max}$ is always larger than the “estimated” value. Therefore, even if the estimated value is shorter than the minimum operating wavelength, the true value of $\lambda_{c,\max}$ may not be, and single-mode operation cannot be guaranteed.

In this paper, we propose a novel simplified cutoff wavelength measurement method for multicore fibers. As in [3,4], the proposed method requires only a single measurement of the spectrum of the entire MCF (all cores) but can additionally derive an upper bound on $\lambda_{c,\max}$. If the upper bound of $\lambda_{c,\max}$ is measured to be shorter than the minimum operating wavelength, then the true value of $\lambda_{c,\max}$ is necessarily shorter than the minimum operating wavelength. We briefly describe the measurement principles and validate the proposed method experimentally.

2. Measurement Principles

The cutoff wavelength λ_c of a single-mode fiber (SMF) is defined as the wavelength greater than which the ratio Δa between the total power P_{tot} , including launched higher order modes (HOMs), and the fundamental mode power P_{op} has decreased to less than 0.1 dB [5], under substantial and uniform excitation of both LP_{01} and LP_{11} modes. Around λ_c , the power ratio Δa can be expressed as

$$\Delta a(\lambda) = 10 \log_{10} [P_{\text{tot}}(\lambda)/P_{\text{op}}(\lambda)] \approx 10 \log_{10} \{ [P_{\text{op}}(\lambda) + P_c(\lambda)] / P_{\text{op}}(\lambda) \} = 10 \log_{10} [1 + \rho(10^{-\alpha_c(\lambda)/10})], \quad (1)$$

where P_c is the power of the lowest-order HOMs contributing to λ_c (hereinafter referred to as cutoff modes), ρ is the ratio of the number of cutoff modes to the number of operating modes (one fundamental mode in SMFs), and α_c is the attenuation in dB of the cutoff modes. All parameters correspond to the length of a test fiber (or core) sample. In the standard SMF case, $\rho = 2$ (two degenerate LP_{11} vs. one LP_{01}) and $\alpha_c \approx 19.3$ dB at $\Delta a = 0.1$ dB. In MCF, λ_c of each core is measured using a method consistent with SMF: light is launched into and received from only one core, and λ_c of every core is measured sequentially, one core at a time.

Both in the previous method [3,4] and in the present method, light is launched into and received from all modes of all cores simultaneously for simplified measurement. The differences between the two methods are that the present method (i) assumes that the test light is uniformly distributed among all modes of all cores of the sample MCF, and (ii) derives an upper bound on $\lambda_{c,\max}$ that is in principle equal to or longer than the true $\lambda_{c,\max}$ of an MCF. When the test light is equally distributed among all modes of all cores, the power ratio Δa_{MC} between the total power and the fundamental mode power of the MCF can be expressed as

$$\Delta a_{\text{MC}}(\lambda) \approx 10 \log_{10} \frac{\sum_n P_{\text{op},n}(\lambda) + \sum_n P_{c,n}(\lambda)}{\sum_n P_{\text{op},n}(\lambda)} \approx 10 \log_{10} \left[1 + \frac{\rho}{N} \sum_n 10^{-\alpha_{c,n}(\lambda)/10} \right], \quad (2)$$

where N is the number of the cores of the MCF, and $n \in \{1, \dots, N\}$ in subscripts is the core identification number. Using the trivial relationships $(\sum x_n)/N \leq \max(x_n)$, $(1+x)^N \geq 1+Nx$, $\sum x_n \geq \max(x_n)$, which hold when $x_n \geq 0$, we can derive:

$$\Delta a_{\text{MC}}(\lambda) \leq 10 \log_{10} \left\{ 1 + \rho \max_n \left[10^{-\alpha_{c,n}(\lambda)/10} \right] \right\} \leq N \Delta a_{\text{MC}}(\lambda). \quad (3)$$

The middle term of (3) is equivalent to Δa of the core with the highest P_c , or equivalently the lowest α_c and maximum λ_c . Therefore, (3) can be rewritten as

$$\lambda|_{\Delta a_{\text{MC}}=0.1 \text{ dB}} \leq \max_n \lambda_{c,n} \leq \lambda|_{N \Delta a_{\text{MC}}=0.1 \text{ dB}}. \quad (4)$$

and we can assign the LHS and RHS of (5) as the lower bound ($\lambda_{c,\text{max,lb}}$) and upper bound ($\lambda_{c,\text{max,ub}}$) of the maximum λ_c from the single spectrum Δa_{MC} . Figure 1 shows example behavior of Δa_{MC} in MCFs. When λ_c of one core is much longer than that of the other cores, Δa of the core with the maximum λ_c approaches $N \Delta a_{\text{MC}}$, as shown in Fig. 1(a). When all cores have equal λ_c , Δa 's of the individual cores overlap with Δa_{MC} , as shown in Fig. 1(b).

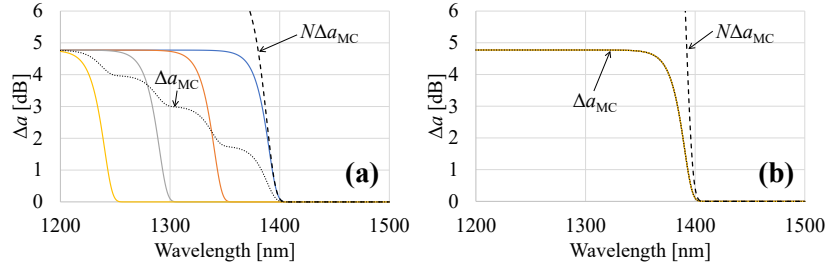


Fig. 1. Calculated examples of the spectra Δa of the ratio between the total power and the fundamental mode power of two hypothetical 4-core fibers. Solid lines: Δa of the individual cores, dotted line: Δa_{MC} , and dashed line: $N \Delta a_{\text{MC}}$. (a) λ_c 's of the four cores are unique (1400 nm, 1350 nm, 1300 nm, 1250 nm). The solid Δa line with the maximum λ_c approaches the dashed $N \Delta a_{\text{MC}}$ line at around $\Delta a = 0.1$ dB. (b) λ_c 's of the four cores are identical (1400 nm). All four solid Δa lines overlap with the dotted Δa_{MC} line.

3. Experimental Validation

To validate the proposed method, we performed λ_c measurements of a 2-core MCF and a trench-assisted 4-core MCF designed according to the MCFs in [6–8]. The core pitch was measured to be 35.9 μm for the 2-core MCF and averaged 39.7 μm for the square core layout of the 4-core MCF. The average mode field diameter of the fundamental mode was 11.4 μm at $\lambda = 1550$ nm for the 2-core MCF and 8.6 μm at $\lambda = 1310$ nm for the 4-core MCF. The λ_c measurement procedure essentially followed the reference test method for the cable cutoff wavelength λ_{cc} of a 22 m fiber sample outlined in Rec. ITU-T G.650.1 section 6.3.2 [5]. We employed the multimode reference method to obtain the spectral attenuation of an individual core of the MCF with full-mode excitation, or the entire MCF with full-mode full-core excitation. The measured spectral attenuation was used to derive Δa , the spectrum of the power ratio between P_{tot} and P_{op} . As a reference, λ_{cc} of each core of the MCFs was measured using a launching MMF with a 30- μm core diameter (MMF-30) optically aligned to a single core of the MCF at a time. In the proposed method, light is launched into all cores of the MCF under test via a launching MMF with a core diameter of 105 μm and a numerical aperture (NA) of 0.22 (MMF-105). The NAs of MMF-30 and MMF-105 are sufficiently higher than the NAs (0.12–0.13) of the cores of the sample MCFs. The output field of MMF-105 has a top hat profile and a field diameter large enough to excite all modes of all cores uniformly (examples of the intensity profiles at 1550 nm are shown in Fig. 2). The peak intensity difference of the output profiles among the MCF cores was within $\pm 1\%$ for the 2-core fiber and within $\pm 1.5\%$ for the 4-core fiber. Because light is both launched into and received from all cores, the proposed measurement method requires only one measurement, regardless of the number of cores. Furthermore, simple cladding-based alignment, such as using a v-groove, between the MMF and MCF under test is sufficient.

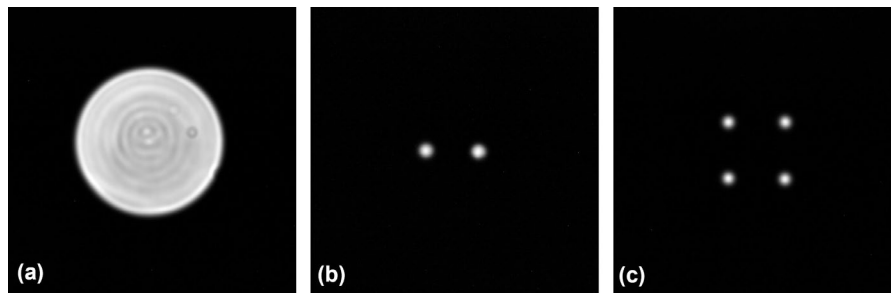


Fig. 2. Infrared camera images (200 $\mu\text{m} \times 200 \mu\text{m}$) of the output intensity profiles at 1550 nm of (a) the launching MMF, (b) the 2-core MCF, and (c) the 4-core MCF.

These features greatly simplify the cutoff measurement procedure compared to individual core measurements, where the launching fiber or optics must be aligned to each core of the MCF, and the number of measurements increases with the number of cores. The large-diameter, high-NA core MMF used in this study may be replaced by suitable large spot, large NA optics that can excite substantially and uniformly both the LP₀₁ and LP₁₁ modes of all MCF cores.

The λ_{cc} measurement results of the 2-core and 4-core MCFs are shown in Fig. 3 and Table 1. Figure 3 illustrates the Δa_{MC} spectra measured simultaneously from all cores and the Δa spectra measured from each core individually. Table 1 summarizes the resulting λ_{cc} obtained from Δa and the bounds of the maximum λ_{cc} ($\lambda_{cc,max}$) derived from Δa_{MC} . As predicted by theory, the measured Δa for the core with the maximum wavelength is bounded from below by Δa_{MC} and from above by $N\Delta a_{MC}$, within measurement error. Thus, $\lambda_{cc,max}$ is bounded by $\lambda_{cc,max,lb}$ and $\lambda_{cc,max,ub}$ obtained from the measured Δa_{MC} , for both the 2-core fiber and the 4-core fiber.

In the 2-core fiber, due to a difference in Δa between its two cores, the Δa_{MC} spectrum near $\lambda_{cc,max}$ (core 1) is determined primarily by core 1 and sees little influence from core 2 with its much lower λ_{cc} . Therefore, Δa_{MC} is approximately equal to $(1/N)\Delta a_{Core 1}$ (i.e., $N\Delta a_{MC} \approx \Delta a_{Core 1}$) near $\lambda_{cc,max}$, and the upper limit of the $\lambda_{cc,max}$ range is quite tight ($\lambda_{cc,max} \approx \lambda_{cc,max,ub}$). The difference between $\lambda_{cc,max,lb}$ and $\lambda_{cc,max,ub}$ for the 2-core fiber is about 4 nm. For the 4-core fiber, the bounded range of $\lambda_{cc,max}$ ($\lambda_{cc,max,lb} - \lambda_{cc,max,ub}$) is wider (10 nm) due to higher core count and relatively shallow slope of Δa , compared to the 2-core fiber. Because λ_{cc} and Δa are roughly the same between core 3 and 4, the Δa_{MC} spectrum near $\lambda_{cc,max}$ is affected by both cores, so $\Delta a_{MC} \approx (2/N)\Delta a_{Core 3} \approx (2/N)\Delta a_{Core 4}$ near $\lambda_{cc,max}$, and the actual $\lambda_{cc,max}$ falls roughly at the midpoint of $\lambda_{cc,max,lb}$ and $\lambda_{cc,max,ub}$. For both fibers, the measured $\lambda_{cc,max}$ bounds hold, confirming the measurement theory.

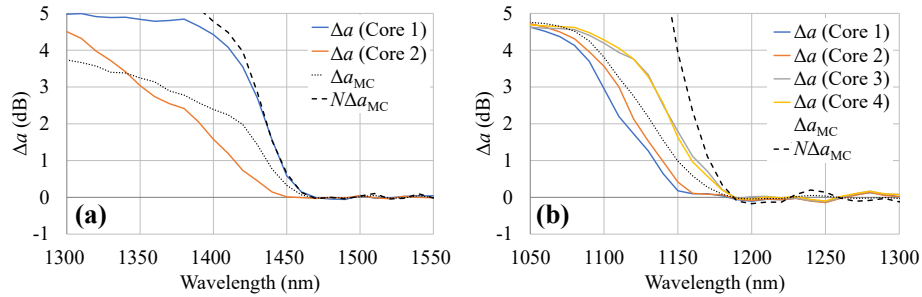


Fig. 3. Spectrum of the total power to fundamental mode power ratio of the (a) 2-core MCF and (b) 4-core MCF obtained with the multimode reference method.

Table 1. MCF cutoff wavelength measurement results

Sample	λ_{cc} obtained by individual core measurement (nm)					Upper & lower bounds of $\lambda_{cc,max}$ obtained by the proposed single spectrum measurement method	
	Core 1	Core 2	Core 3	Core 4	$\lambda_{cc,max}$	$\lambda_{cc,max,lb}$	$\lambda_{cc,max,ub}$
2-core MCF	1462	1442	--	--	1462 (Core1)	1458	1462
4-core MCF	1154	1161	1186	1186	1186 (Cores 3&4)	1179	1189

4. Conclusion

We proposed an MCF cutoff wavelength measurement method that bounds the maximum cutoff wavelength with a single measurement of combined spectral attenuation across all cores. Experimental measurements conducted on a 2-core MCF and 4-core MCF using the proposed method have validated our theoretical model. The proposed method enables reliable measurement of the cutoff wavelength in MCFs, ensuring single-mode operation within a wavelength range longer than a predetermined minimum operating wavelength. Additionally, it allows for the straightforward launching and reception of test light for the entire MCF without the need for individual core alignment. The proposed method will facilitate simple and efficient inspection of MCFs and promote broader adoption of MCFs across diverse applications.

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