Determination of the effective cut-off wavelength of several single-mode fiber patchcords

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Abstract. The effective cut-off wavelength is one of the important parameters in single-mode optical fiber. Nevertheless, the data sheet of an optical fiber patchcord generally does not specify the exact value of the cut-off wavelength. However, for certain applications, for example, to know the value of the numerical aperture, core radius and refractive index of the fiber at a certain wavelength, the exact value of the cut-off wavelength should be known. In this paper, we report the measurement of the cut-off wavelength of several commercially-available single-mode fiber patchcords, namely, the 780HP, SMF28, SM600, and SM2000. We used the multi-mode reference method in our measurement because it is simpler than the bend reference counterpart. From our measurements, the effective cut-off wavelengths for the above-mentioned fiber patchcords are (0.731±0.006) µm, (1.225±0.005) µm, (0.485±0.010) µm, and (1.665±0.018) µm, respectively, and its comparison with catalogue values has been discussed. The usefulness of the cut-off wavelength determination for calculating other fiber parameters has also been described.

1. Introduction
The cut-off wavelength (λc) is the wavelength above which a fiber behaves as a single-mode fiber [1, 2]. The theoretical cut-off wavelength of an optical fiber depends on the radius and refractive index of the fiber core, the normalized frequency, the relative refractive index between core and cladding, and the fiber numerical aperture (NA) [1, 2]. Nevertheless, the data sheet of an optical fiber generally does not specify the exact value of the cut-off wavelength whereas for certain application, for example, in an intensity-based sensor which utilized bending loss effect, cut-off wavelength highly determines the bending loss. The differences in core radius or NA of about 5% can result in bending losses that differ by more than one order of magnitude [3], while according to Schermer and Cole [4], the numerical aperture of SMF28 in the data sheet varies between 0.12 and 0.14. The cut-off wavelength value can also be used to calculate several fiber parameters such as core and refractive index of the fiber core and the fiber’s NA [4, 5]. Thus, an exact value of cut-off wavelength in optical fiber applications is important.

There are many techniques for cut-off wavelength measurement [1, 6 – 9], among other is bend reference method where the long wavelength edge of the bend-induced loss is greater than the long-wavelength baseline by 0.1 dB and the effective cut-off wavelength can be determined from the point of intersection of a straight line parallel to the λ-axis and displaced by 0.1 dB from the long-wavelength baseline. Another technique is the multi-mode reference technique where transmission
powers in a single-mode and a reference multi-mode fiber are compared to determine the effective cut-off wavelength.

In this paper, we report the measurement of the cut-off wavelength of several commercially-available single-mode fiber patchcords, namely, the 780HP, SMF28, SM600, and SM2000 patchcords. We use the multi-mode reference method in our measurement because it is simpler and no need to introduce the bending to the fiber.

2. Method
Fiber cut-off wavelength has been defined by the ITU-T G650 [10] which is obtained from measurement with bending reference technique using 2 m length of fiber with 14 cm single loop radius. As stated before, there are many techniques for measuring the cut-off wavelength and basically, it involves the comparison of transmitted power from the test fiber to the reference fiber at different wavelengths [6 – 9]. In the bend reference technique, the reference fiber is the same sample of single-mode fiber which is coiled to several diameter values. In the multi-mode reference technique, a multi-mode fiber is used as a reference fiber.

Figure 1. The multi-mode reference technique set-up.

The multi-mode reference technique is presented by the experimental set-up shown in figure 1. The white light source was launched into the test single-mode fiber and the spectral variation of its output power, $P_s(\lambda)$ is recorded by an optical spectrum analyzer. Then, the single-mode test fiber is replaced by a multi-mode fiber and the spectral dependence of power $P_m(\lambda)$ is again recorded. The variation of loss $R_m(\lambda)$ is the comparison output of both spectrum, the $P_s(\lambda)$ and $P_m(\lambda)$, which is given as below [1].

$$R_m(\lambda) = 10 \log \left[ \frac{P_s(\lambda)}{P_m(\lambda)} \right]$$

(1)

To find the cut-off wavelength, firstly the $R_m$ is plotted as a function of $\lambda$. A straight line is then fitted to the long wavelength region of $R_m(\lambda)$ and shifted up to 0.1 dB. The wavelength value at the point of intersection of this line with the $R_m(\lambda)$ curve gives the effective cut-off wavelength (figure 2).

Figure 2. Determination of the cut-off wavelength with the multi-mode reference technique.
As mentioned before, the test single-mode fibers used here are the 780HP, SMF28, SM600, and SM2000 fiber patchcords from Thorlabs Inc. [11] with a length of 2 m each. The multi-mode fiber used for the reference is the M31L02 from Thorlabs Inc. which has a core diameter of 62.5 µm and NA of 0.275 [11]. The white light source is a stabilized broad band light source type SLS201/M (Thorlabs) while the optical spectrum analyzer/OSA is the AQ6310B model from ANDO.

Interestingly, the cut-off wavelength ($\lambda_c$) value can be used to determine other fiber parameters such as core radius ($a$) and numerical aperture (NA) of a single-mode fiber. The fiber data sheet rarely informs the value of the core radius but, instead, its mode field diameter (MFD) value at a certain operating wavelength ($\lambda$). To determine the value of $a$, we use an empirical formula derived by Marcuse [5].

\[
MFD = 2a \left( 0.65 + 0.434 \left( \frac{\lambda}{\lambda_c} \right)^{3/2} + 0.015 \left( \frac{\lambda}{\lambda_c} \right)^{6} \right)
\]

Furthermore, the value of NA can be calculated using the cut-off wavelength expression which is given by [1, 2]:

\[
\lambda_c = \frac{2\pi a}{V} \sqrt{n_1^2 - n_2^2}
\]

or

\[
\lambda_c = \frac{2\pi a}{2.405} NA
\]

because $NA = \sqrt{n_1^2 - n_2^2}$, $a$ is the radius of the core, $n_1$ is the refractive index of the core, and $n_2$ is the refractive index of the cladding. Equation 3 and 4 are derived from the equation for the normalized frequency $V$ of the fiber written as:

\[
V = \frac{2\pi}{\lambda} aNA
= \frac{2\pi}{\lambda} n_1 (2\Delta)^{1/2}
\]

Where $\Delta = \frac{1}{2} \frac{n_1^2 - n_2^2}{n_2^2}$ is the relative index difference, and $V = V_c = 2.405$ (the first root of the $J_0$ Bessel function) is the normalized frequency for the cut-off condition for a single-mode fiber.

3. Results and discussion
Figure 3a shows the typical result of the variation loss curve, $R_m(\lambda)$, for the 780HP fiber patchcord at a wavelength range from 680 nm to 760 nm. Figure 3b shows the detailed graph for the cut-off wavelength determination which results in the effective cut-off wavelength value of 730 nm from the intersection point. Similarly, the variation losses with their determinations of effective cut-off wavelengths for the SMF28, SM600 and SM2000 fiber patchcords, respectively, are presented in figure 4 – 6. Table 1 presents the results of our cut-off wavelength measurement, the calculated of the core radius, the numerical aperture of each fiber patchcords, and the catalogue value for comparison.
Figure 3(a). The plot of variation loss and the determination of cut-off wavelength for the 780HP fiber patchcord. (b). Details of its cut-off wavelength determination result in intersection point at wavelength 730 nm ($\lambda_c$).

Figure 4. The plot of variation loss as a function of wavelength for the SMF28 fiber patchcord with its cut-off wavelength determination.
Figure 5. The plot of variation loss as a function of wavelength for the SM600 fiber patchcord with its cut-off wavelength determination.

Figure 6. The plot of variation loss as a function of wavelength for the SM2000 fiber patchcord with its cut-off wavelength determination.

Table 1. Comparison of the measured cut-off wavelength, the calculated core radius and numerical aperture with its catalogue values.

| Type of patchcord | Operating wavelength [11] (µm) | Cut off wavelength, $\lambda_c$ (µm) | Calculated core radius$^a$ (µm) | NA $^b$ | Calculated$^b$ | Catalogue value [11] |
|-------------------|--------------------------------|-----------------------------------|--------------------------------|--------|--------------|---------------------|
| 780HP             | 0.780 – 0.970                  | (0.731±0.006)                     | (0.730±0.030)                  | 2.03   | 0.14         | 0.13                |
| SMF28             | 1.260 – 1.625                  | (1.225±0.005)                     | <1.260                         | 3.91   | 0.12         | 0.14                |
| SM600             | 0.635 – 0.780                  | (0.485±0.010)                     | 0.500 – 0.600                  | 1.93   | 0.09         | 0.1 – 0.14          |
| SM2000            | 1.700 – 2.300                  | (1.665±0.018)                     | 1.700                          | 5.14   | 0.12         | 0.11                |

$^a$ Calculated using equation 2.
$^b$ Calculated using equation 4.

The cut-off wavelength measurement shows that the experimental values for all the fiber patchcords are comparable or still within the range of its catalogue values. By using this obtained effective cut-off wavelength, we can then calculate the core radius and the numerical aperture of the fiber, as presented in table 1. This calculation is important because relying merely on the catalogue
value, would give confusing results. For example, as pointed out by Schermer and Cole [4], the catalogue values for SMF28 fiber are as follows: core diameter 8.2 µm, refractive index difference 0.36%, and the numerical aperture 0.14. Using these values, we obtained NA = 0.123, calculated from equation 5, and λc = 1.49 µm, calculated from equation 4, that would imply multi-mode behavior at 1.31 µm, which is not true because this type of single-mode fiber is designed to operate at 1.3 – 1.5 µm. Caution should be given because the catalogue value of NA is typically based on beam output measurement which is different with the index-based NA; and the refractive index difference is usually measured in the fiber preform, rather than in the fiber itself [4].

4. Conclusions
By using the multi-mode reference method, we have determined the effective cut-off wavelength of four commercially available fiber patchcords, namely, the 780HP, SMF28, SM600, and SM2000. The data sheet of each fiber does not mention the specific value of its cut-off wavelength. The average value of the effective cut-off wavelength for each fiber patchcords is 0.731, 1.225, 0.485, and 1.665 µm, respectively. Furthermore, from the calculation of the fiber core radius, we obtained that the core radius of the SM2000 > SMF28 > 780HP > SM600, as expected from its operating wavelength.

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