Comparative study of the effective single mode operational bandwidth in sub-wavelength optical wires and conventional single-mode fibers

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Abstract: We present the first experimental comparison of effective single mode operation bandwidth in sub-wavelength optical wires (SOWs) and conventional single-mode fibers (SMFs). The full transmission spectrum, half-turn bend loss and mode field diameter were measured and compared for a variety of SMFs of different cut-off wavelength and a SOW. The SOW was shown to offer an enormously broadband single-mode operation bandwidth with a larger mode field area than the SMFs. Applications of SOWs include fiber lasers, sensors, photolithography and optical coherence tomography amongst others.

OCIS codes: (230.1150) All-optical devices; (060.2340) Fiber optics components; (220.4000) Microstructure fabrication; (220.4241) Nanostructure fabrication.

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1. Introduction

Over the past few decades, standard single-mode fibers (SMFs) have been used widely within optical communication systems to transmit high data rate signals with the greatest focus on the near infrared spectral range (1260~1675 nm) due to the relatively low loss in this wavelength range [1]. However, in recent years there has been a continuously growing need for single mode operation at shorter wavelengths (400~1260 nm) driven largely by advances in high-sensitivity optical sensors, lasers, spectroscopy, photolithography, aerospace, defense and biomedical imaging systems [2,3]. Standard single mode fibers are designed to have cutoff wavelength around 1.26 μm and the development of specialty single mode fibers with short

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wavelength cutoffs is necessary. There are few kinds of commercial specialty fibers that can provide a short-wavelength cutoff – referred to by several different names such as “Select cutoff SMF”, “Visible fiber” and “RGB fiber”. Unfortunately, engineering a short wavelength cutoff inevitably requires fibers designs characterized by a very small core diameter and a relatively small refractive index difference (Δ) between core and cladding. This fact leads to weaker mode field guidance and increases the external bend sensitivity of the fiber at long wavelengths, which results in notably reduced operating spectral window. For example, SMF with a cutoff wavelength of 780 nm (Nufern 780HP) has a 5µm core diameter and can be operated within a very limited spectral region extending from just 780 to 970nm. Compared with conventional telecom SMF (Corning SMF28), this single mode operational bandwidth is considerably reduced from 415nm to 190nm. The bandwidth can be substantially less than 100nm when the cutoff wavelength is further shifted to shorter wavelengths. Furthermore, the reduced core diameter and numerical aperture dictate the need for high-precision core alignment processes when splicing and can result in both fiber handling and power penalty problems within many practical applications.

The authors have recently proposed and successfully demonstrated the use of extremely thin sub-wavelength optical wires (SOWs) [4–6] as an efficient way to provide higher-order mode filtering in multimode waveguides [7,8] and have shown that this can be used to obtain broadband single-mode operation of a fiber at short wavelengths, or over a wide range of wavelengths. The approach relies simply on filtering higher order modes in a multimode waveguide by integrating a single-mode SOW section within the fiber which incorporates specific taper transitions (adiabatic for fundamental mode but non-adiabatic for higher-order modes) that minimize re-excitation of the filtered modes. This can greatly enhance the single-mode operation of the multimode fiber while still maintaining large mode field in the lengths of fiber both before and beyond the SOW. In this study, we have experimentally compared the single-mode operational bandwidth of a SOW with several commercial SMFs developed and sold for short-wavelength applications. The full transmission spectrum, half-turn bend loss and mode field diameter of each fiber was tested and compared with those of the SOW. The SOW was found to offer an enormously broadband single-mode operational bandwidth relative to the SMFs. The large mode field area and robust stability of single mode operation should prove beneficial for various applications in fiber lasers, sensors, photolithography and optical coherence tomography.

2. Optical characterization of the SOWs and conventional SMFs

A schematic diagram illustrating the principle of higher-order mode filtering using a SOW is summarized in Fig. 1. As described in reference 7, the higher-order modes present at the input fiber can be effectively suppressed by controlling the biconical taper transition profile (by ensuring an adiabatic transition for LP_{01} but non-adiabatic transition for higher-order modes) and the diameter of the SOW in the waist region. This suppresses the propagation of higher-order modes along the entire length of the SOW and constrains the number of guided modes [7]. As shown in Fig. 1b, a standard telecom SMF (Corning SMF28) shows abrupt and discrete transmission power drops near the cutoff wavelengths ($\lambda_c\_LP_{11}$, $\lambda_c\_LP_{21}$, $\lambda_c\_LP_{02}$) and the single mode operational bandwidth is restricted by the higher-order mode cutoffs at short wavelengths. With a SOW, however, all higher-order modes are strongly attenuated or stripped out of the fiber and a pure single mode beam is obtained over a broad spectral window (400~1700nm). No higher-order mode cutoffs are observed in the transmitted spectrum at any wavelength (Fig. 1c).

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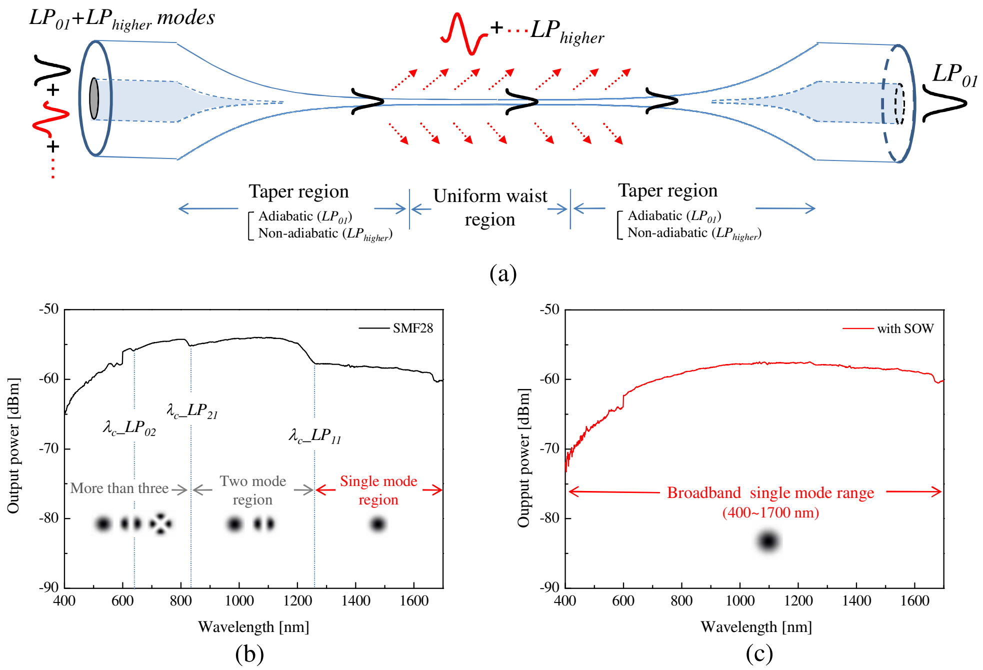
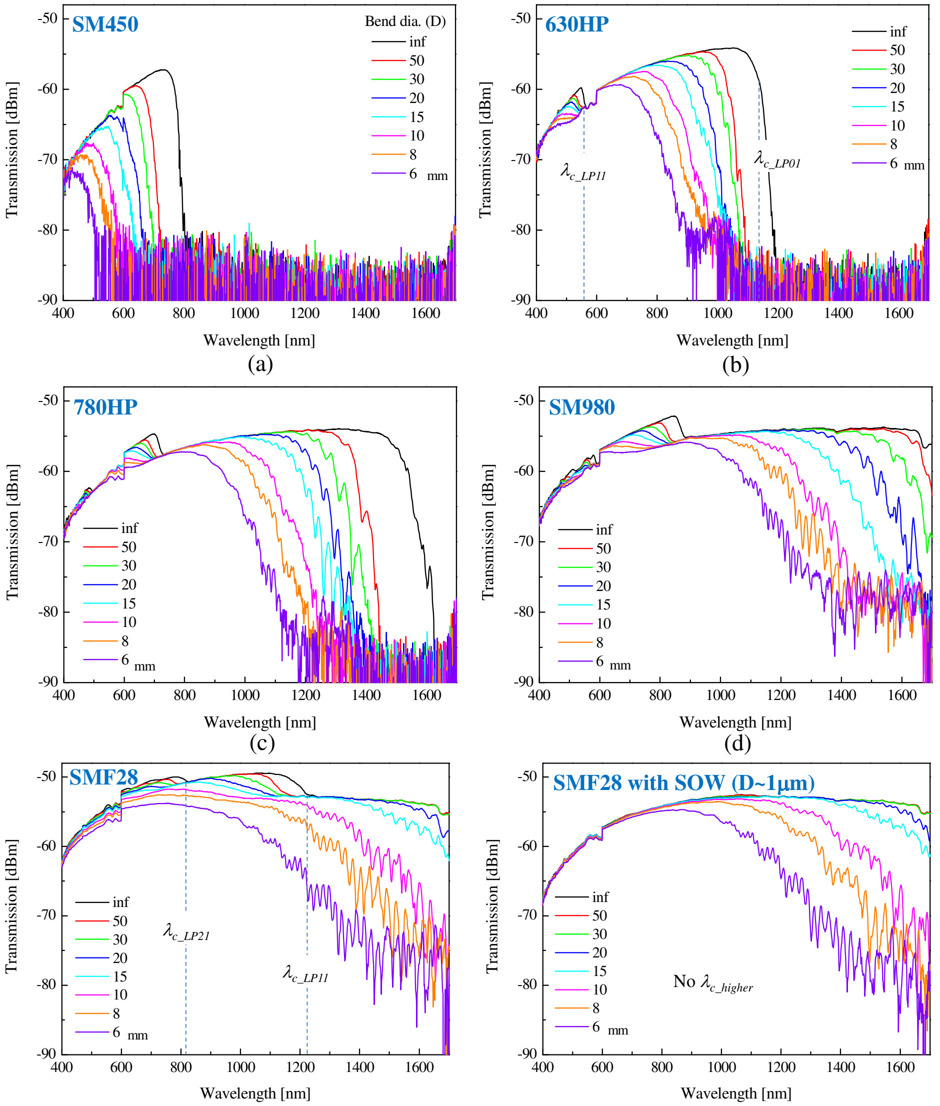


Fig. 1. (a) Schematic diagram of the sub-wavelength optical wire (SOW) for higher-order mode filtering. The biconical SOW with specially designed transition taper and very-thin taper waist effectively suppresses any higher-order modes at the fiber input and provide broadband single mode operation at the output. The transmission spectra of standard telecom fiber at the input (b) and output (c) are also compared.

2.1 Transmission spectra and bend losses

In order to experimentally quantify and compare the single mode operation bandwidth of a SOW with several commercial SMFs, the full transmission spectra and bend loss properties were examined using an incoherent white light source and an optical spectrum analyzer. In our experiment, the SMFs have various higher-order mode cutoff wavelengths ranging from 450nm to 1260nm and core diameters between 3.3µm and 8.3µm. As shown in Fig. 2, the single-mode operational bandwidth is limited by the higher-order mode cutoff ($\lambda_{c\text{-}LP11}$) at short wavelengths and by the fundamental mode cutoff ($\lambda_{c\text{-}LP01}$) at long wavelengths. For a short-wavelength cutoff SMF, a relatively small core diameter and a low refractive index difference (Δ) between core and cladding lead to weaker mode field guidance and result in increased bending sensitivity for the fiber in the long wavelength region, which results in a noticeably reduced operational spectral window. For example, SMF with a cutoff wavelength of 630 nm (Fig. 2b) has a 4µm core diameter and can be operated within limited spectral region extending from 600 to 770nm. This single mode operation bandwidth (170nm) is considerably smaller than the 415nm bandwidth observed in conventional telecom SMF (Fig. 2e). The bandwidth can be less than 100nm when the cutoff wavelength is further shifted to shorter wavelengths. Another noticeable point is that for the 1µm SOW there is no higher-order mode cutoff as observed in the SMFs and the optical bandwidth is simply limited by the bend loss edge of the fundamental mode at the long wavelength. The SOW, as previously discussed, provides a significant enlargement of the optical bandwidth and can be used for short-wavelength or broadband single-mode operation. When reducing the bending curvature, some spectral transmission oscillations are observed near the bend loss edges. It is mainly due to the coupling between the fundamental core mode and whispering gallery cladding modes due to light reflection from the boundary of the coating/air and cladding/coating interfaces [9].



(a) (b)

(c) (d)

(e) (f)

Fig. 2. Full transmission spectra and bend loss properties of various kinds of short-wavelength cutoff SMFs and a SOW. For a 1μm SOW, there is no higher-order mode cutoff as observed in the SMFs at short wavelengths and the bandwidth is limited simply by the bend loss edge of the fundamental mode at long wavelength.

For a more visual representation of the data, we have produced a comparison chart that highlights the effective single mode operation bandwidths of a SOW and several commercial SMFs as shown in Fig. 3. The higher-order cutoff wavelengths of the fibers are determined by the transmitted power method in accordance with the TIA standard [10] and bend loss edges of the fundamental mode are established by assuming a maximum tolerable bend loss of 3-dB. As expected, the single mode range of commercial SMFs is limited by two cutoff wavelengths ($\lambda_{c\text{-}LP01}$, $\lambda_{c\text{-}LP11}$) and which is easily influenced by the bend diameter. For the case of SM980 (Fibercore inc.), the optical bandwidth is decreased from 815nm to 277nm as the bending diameter decreases from infinite to 6mm. For practical handling conditions and applications, a 10mm bending diameter tolerance is required however SM980 fiber provides only 427nm optical bandwidth at this bend diameter. Other SMFs also show very restricted optical bandwidths for these bending conditions, i.e. SM450 (135nm), 630HP (296nm), 780HP (389nm), SMF28 (384nm). Note that a 1μm SOW presents a bandwidth greater than 954nm from 400nm to 1354nm, which is three to four times larger than the SMFs. We expect that the wideband single mode operation can be further enhanced with bend-robust fibers [11].

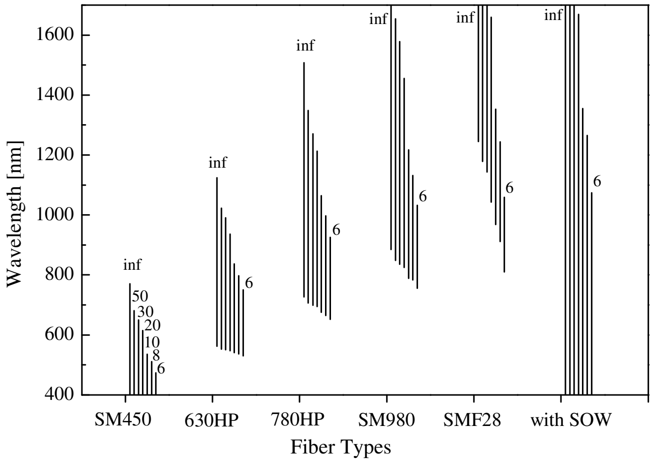


Fig. 3. Comparison between the effective single-mode operation bandwidths of several SMFs and a telecom fiber with a SOW filter for different bend diameters.

2.2 Mode field diameter (MFD)

In order to compare the mode field diameter of the fibers, we first calculated the effective mode field diameters from the data sheet of the fibers and a commercially available optical fiber design program (Optiwave Optifiber). As depicted in Fig. 4, the MFD obtained from the

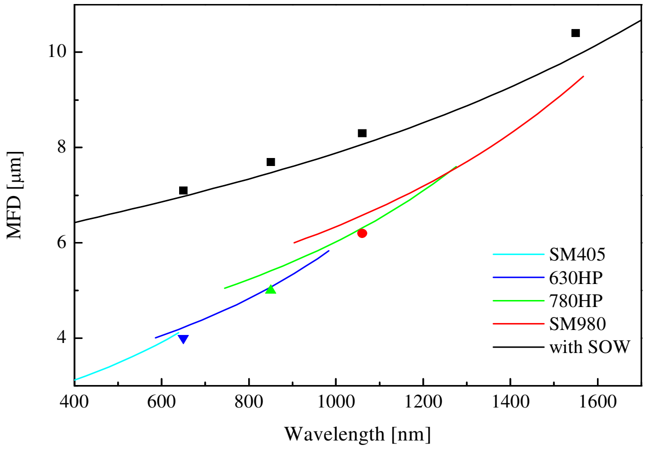


Fig. 4. Measured (symbol) and simulated (line) mode field diameter comparison for several SMFs and for a telecom fiber with a SOW filter.

SOW is roughly two times larger than those of the short-wavelength cutoff SMFs. This is mainly due to the fact that the SOW is made in SMF28 fiber, which has a relatively large core diameter and refractive index difference. In addition, we experimentally measured the MFD by analyzing the far-field radiation pattern emerging from the fibers (symbols) and compared with the simulated results in Fig. 4 (continuous lines) [12]. The measured MFDs agree well with the simulated results and the distinctive large diameter of the SOW at short-wavelengths is confirmed.

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2.3 Bending loss measurement of different LP modes in fibers

The higher-order mode-filtering feature of a SOW can provide another useful function to separately measure the bending loss of individual *LP* modes in fibers. In Fig. 2(e), the optical bend loss measurement in the dual mode operation region (830~1260nm) of the telecom fiber involves both the fundamental LP_{01} and the second-order LP_{11} mode (SMF: LP_{01} + LP_{11}). However, in Fig. 2(f), a SOW eliminates the LP_{11} mode, permitting selective observation of the LP_{01} mode (SOW: LP_{01}). Therefore, we can get separate information about the bending properties of LP_{01} and LP_{11} by comparing the measured data. The measured bend loss coefficients of the LP_{01} and LP_{11} mode for wavelength of 0.9, 1.0 and 1.1μm are shown in Fig. 5 (symbols) and compared with the simple formula (lines) introduced in Ref. 13. It has been found that the LP_{11} mode shows higher bend loss at the same bend diameter but a lower attenuation slope. The technique can be further extended to higher-order mode analysis by developing and optimizing an adiabatic taper shape for fundamental and selected higher-order modes.

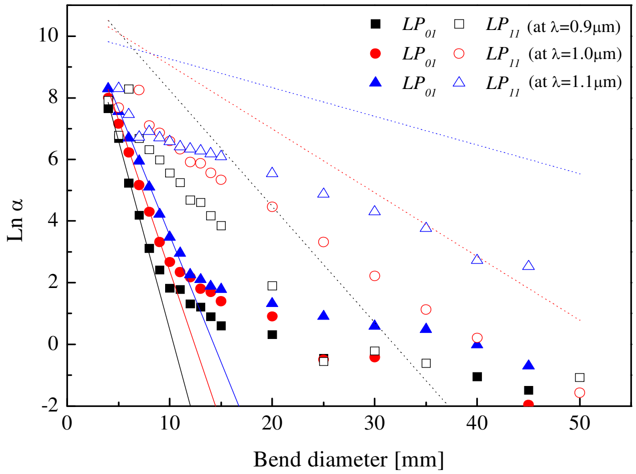

Fig. 5. Comparison of bending loss coefficients for LP_{01} and LP_{11} mode in the telecom SMF (Corning SMF28): symbols and continuous lines represent experiments and simple model of Ref. 13, respectively.

3. Conclusion

In this paper we have presented a comparative study of the effective single-mode operational bandwidth of a SOW with several commercial SMFs. The full transmission spectrum, half-turn bend loss and mode field diameter were characterized and the SOW showed an enormously broadband single-mode operation bandwidth with larger mode field area relative to the SMFs. The peculiar characteristics provide a new means to increase the spectral operation bandwidth of several fiber optic components, in many cases limited only by the intrinsic nature of the fundamental mode in the fibers used. Additionally, the higher-order mode filtering feature of a SOW can provide a useful route to separately measure the bending loss of individual *LP* modes in fibers.

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