High-sensitivity broadband micro-Michelson-interferometer based on an end-sphered hollow-core fiber

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Abstract: We demonstrate a high-sensitivity broadband micro-Michelson fiber interferometer using a singlemode fiber end-spliced with a short (43.9μm) hollow-core end-collapsed lensed fiber. The extinction ratio can be above 25 dB over the 1250-1650 nm wavelength range.

OCIS codes: (060.2340) Fiber optics components; (260.3160) Interference; (280.4788) Optical sensing and sensors.

1. Introduction

Fiber Michelson interferometers (FMI) had been extensively employed in precision sensing applications, especially in displacement and curvature measurement, optical Doppler velocimetry, and optical coherence tomography (OCT) [1,2]. The measurement with high accuracy is actually based on low coherence lights (broadband white lights) which enable the interference to occur only within a very short optical path length difference (OPLD), say a few micrometers, between the sensing and the reference arms. Therefore, the FMI can give rise to a resolution of better than a few micrometers but such FMIs comprising essential broadband components like couplers, polarizers, mirrors, and focus lens are bulky and inefficient. A micro-FMI featured with a compact and monolithic structure is definitely advantageous to provide stable and accurate measurements for harsh environments like in the hollow organs in human body. For micro-FMIs, the interference between two fiber arms is known to be capable of being replaced by the core mode and the excited cladding modes which can be efficiently generated by abrupt tapers [3] or the misalignment between two splicing cores [4]. Using a singlemode fiber mated with a hollow-core optical fiber (HOF) is also a good option [5]. The core mode is partially blocked at the core/air interface whereas the cladding modes are reflected after traveling through a longer optical path length along the cladding. Once the OPLD between the core mode and the coherent cladding modes satisfy the π phase shift, the destructive interferences can be achieved. The induced OPLD in micro-FMIs usually occurs within a physical length of less than a few hundreds of micrometers and thus the polarization-controlling devices as well as the 3 dB broadband coupler are unnecessary. In this work, we demonstrate broadband high-sensitivity micro-FMIs with extinction ratio of 25 dB over 1250-1650 nm wavelength using a singlemode fiber (SMF-28) end-spliced with a HOF, shown Fig. 1(a). The HOF has a core diameter (7.1 μm), shown in Fig. 1(b), slightly smaller than that (8.2 μm) of the singlemode fiber. The output end of the HOF is further collapsed, shown in Fig. 1(c), to reduce the numerical aperture (NA) of fiber for converting a hollow bottle light beam toward a solid beam. The solid beam is more practical for sensing than the bottle beam. The collapsed region is also helpful to receive more backscattering lights from the outside. Finally, the collapsed end is fused by arc to form a spherical lens, shown in Fig. 1(d), for efficiently collecting reflection lights from external moving materials under test. The spectral characteristics of the FMI show that the extinction ratios are substantially improved when the fiber lens is formed. The resonant wavelengths are sensitive to the distance, *d*, between the lens and the external moving material under test. It means that the spherical lens has successfully extended the reflection interface from the end of HOF toward the surface of external material and can efficiently collect the backscattering lights from the outside. This novel micro-FMI can be promising for novel micro fiber OCT systems in precision bio-imaging and mechanical diagnosis applications.

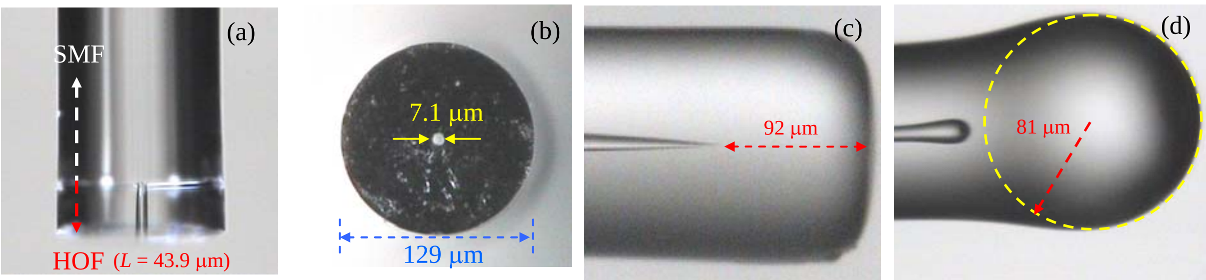

Fig. 1. (a) A singlemode fiber with an end-spliced HOF (L = 43.9 μm). (b) Cross-sectional view of the HOF where the core and cladding diameter is measured as 7.1 μm and 129 μm, respectively. (c) FMI with an end-collapsed HOF (L = 240 μm). (d) FMI with a lensed HOF where the radius of fiber spherical lens is 81 μm.

2. Device structure and fabrications

The working principle of the broadband micro-FMI made of singlemode fiber with an end-spliced lensed HOF is as follows. Fractional amount of the core mode guiding in the SMF-28 is converted into cladding modes when encountering the splicing point between SMF-28 and HOF. This is because the mated HOF has a core diameter slightly smaller than that of SMF-28 to break the core mode into core and cladding modes over the broadband spectral range. But the cladding modes at shorter wavelengths are easier to be excited than that at the longer wavelengths. This could be further optimized by employing the taper-squeeze transition at the SMF/HOF interface, shown in Fig. 1(c), instead of using the drastically changed interface, shown in Fig. 1(a). At the SMF/HOF interface, the core mode is partially reflected by the core/air interface whereas the excited cladding modes are also partially reflected when arriving at the end face of HOF. The reflected cladding modes subsequently interfere with the reflected core mode when passing through the splicing point again. A broadband high reflection coating like silver thin film at the core/air interface and the end of HOF can of course significantly reduce the optical losses of FMI but would be a drawback since the optical path can not be extended to the outside of HOF to vary the OPLD. Moreover, the backscattering signals from the external material under test can not be efficiently collected, either. The mated HOF should be stringently parallel to the SMF-28 since the angular misalignment may degrade the interferences. The OPLD is determined by the length, *L*, of HOF as well as the cladding's index of the HOF. Intuitively, a longer *L* or a higher order cladding mode can induce a smaller free-spectral-range (FSR) between the stopband channels. In addition, tuning the OPLD by moving the external material outside the HOF can control the occurrence of the resonant loss peaks. Therefore, a lensed HOF is definitely crucial for micro-fiber OCT system when a swept laser is employed as a light source to obtain the high-resolution, cross-sectional imaging of the external material. In fabrication, several short, less than a few hundreds of micrometers, HOFs with core and cladding diameters of 7.1 μm and 129 μm are respectively spliced with the SMF-28 fiber and the end of HOF is intentionally collapsed and fused to form a spherical lens by arc. The spectral characteristics of FMI with end-cleaved HOF and with end-sphered HOF are respectively discussed at section 3.1 and 3.2.

3.1 Spectral characteristics of FMI using an end-cleaved hollow core fiber

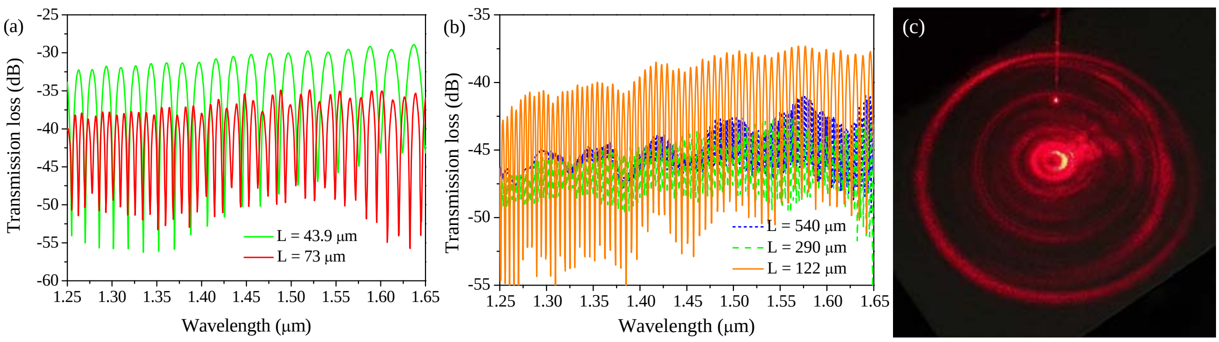

Fig. 2. Transmission spectra of the FMI with an end-cleaved HOF at the length of (a) a few tens of micrometers and (b) a few hundreds of micrometers, RES = 1 nm. (c) The far field mode pattern of end-cleaved HOF with *L*= 240 μm at 635 nm wavelength.

For making a fiber lens at the end of a micro-FMI, a segment of HOF should be end-collapsed before being fused to form a lens by arc. Thus, the influence of *L* on spectral characteristics of FMI should be investigated before a fiber lens is formed. In measurement, a broadband light source comprising multiple superluminescent diodes (SLD) spanning 1250-1650 nm is launched into the lead-in fiber (SMF-28) and the reflected lights are guided to an optical spectrum analyzer (OSA) under the optical resolution (RES) of 1 nm by a 3 dB coupler. For the situations of *L* less than 100 μm, the normalized transmission spectra show that the extinction ratio can reach 25 dB at around 1335 nm, shown in Fig. 2(a). The average losses are higher than 30 dB due to the excitation of cladding modes at splicing point and the partial reflection at the core/air interface and the end face of HOF. However, it is not a serious matter for the fiber OCT system since the quality of detected signals mainly depends on the relative extinction ratios. A high reflection coating can be used to significantly reduce the optical losses when this micro FMI is used as communication components in future works. The FSR, ranging from 7-26 nm, increases with increasing wavelength since the higher order modes are easier to be excited at the shorter wavelengths at the discontinuity junction. So, the OPLD enough for π phase shift can be accumulated more quickly within a short *L*. Fig. 2(b) shows the spectra for the *L* longer than 100 μm, the extinction ratios decrease with longer *L*. This could be resulting from that the splicing between SMF and HOF is not concentric so that the excited leaky cladding modes suffer more losses and lose the phase correlationship after traveling through a longer optical path length. The FSR, the maximum is less than 8 nm, is obviously much narrower that that of the situations in Fig. 2(a). The full width at half maximum (FWHM) for passband channels is typically 2-3 nm which could be further improved for acting as narrowband filters in fiber laser or communication systems. The resonant wavelengths can not be tuned even when an external material, whose index is tunable, is attached against the end of HOF. Fig. 2(c) is the far field mode pattern of the end-cleaved HOF on the screen, 1 cm away from the end of HOF, at 635 nm wavelength. In fact, the central part of the mode patterns for cladding modes at near field is dark but turn out to be bright since most power of the core mode pass through the core/air interface to arrive the screen. Thus, the remained core mode interferes with the cladding modes to produce speckles on the screen. By considering the trade-off between the extinction ratios and length enough for fiber lens, the desired L for FMI is set around 250 μm.

3.2 Spectral characteristics of FMI using an end-sphered hollow-core fiber

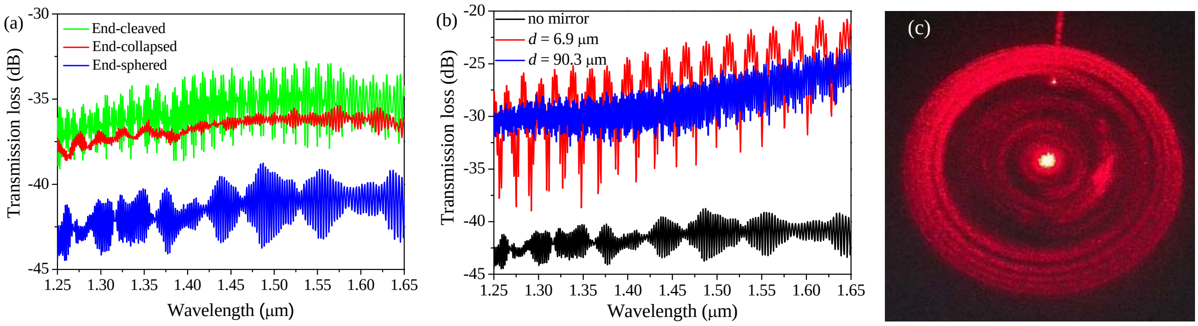

Fig. 3. Transmission spectra of the FMI with an end-sphered HOF (a) at different end shapes and (b) with an external moving mirror, RES = 1nm. (c) Far field mode pattern of the FMI with an end-sphered HOF.

Figs. 3(a) and 3(b) show the evolution of spectral responses of FMI with end-sphered HOF using the sample shown in Fig. 1(d). In Fig. 3(a), the interferences for end-collapsed becomes worse but turned out to be better when the HOF is end-sphered. In Fig. 3(b), an Au-coated reflection mirror is placed right after the spherical lens and the insertion losses are significantly reduced when the mirror is closing to the lens with d = 6.9 μm. The interferences are also improved since more backscattering lights are collected and coupled back into the FMI. When the mirror slightly moved away to be with d = 90.3 μm, the resonant wavelengths and the FSR change accordingly. A longer OPLD can obviously induce a smaller FSR and of course higher insertion losses. The variations of resonant wavelengths, insertion losses, and FSR are important for investigating the d and index of external material for fiber OCT systems. Fig. 3(c) is the far field mode pattern at 635 nm wavelength, with screen 1 cm away from the lens, and it shows that the spherical lens can obviously make the fields of cladding modes more concentrated, even if the 635 nm wavelength corresponds to the multimode condition in SMF-28 fiber. A more perfect fiber spherical lens is expected to achieve a solid light beam for practical sensing applications.

4. Conclusion

We have demonstrated the broadband micro-fiber Michelson interferometer using a singlemode fiber end-spliced with a lensed hollow fiber. The length of hollow fiber is only about 240 μm and the radius of spherical lens is 81 μm. The extinction ratio can be above 25 dB and the resonances occurred all over 1250-1650 nm wavelength. Without the fiber lens, the cladding modes can not reach the external material under testing and then recaptured by the fiber lens to interfere with the reflected core mode. The wavelength shifts of resonances correspond to the moving of external material relative to HOF. This broadband micro-fiber Michelson interferometer is simple, cost-effective, and stable. It is highly promising for the communication components like narrowband filters using end-cleaved hollow fiber and for the micro fiber OCT system using end-sphered hollow core fiber. This interferometer is promising for micro OCT system in a harsh environment such as in the hollow organs in human body.

5. References

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