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Experimental investigation of backreflection at air-core photonic bandgap fiber terminations

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ABSTRACT

Backreflection from the termination of air-core photonic bandgap fibers (PBFs) is experimentally investigated based on a range-extended Mach-Zehnder and Michelson hybrid (M^2) interferometer. For primary waves generated by the fundamental modes, the reflectivity is about −90 dB; for secondary waves caused by other modes, the reflectivity is less than −80 dB when compared to the intensity of the primary wave and −20 to −50 dB when compared to their own incident intensity. To suppress the reflection, ~3-centimeter PBF at the end is filled with alcohol through the capillary effect, and this proposed method is shown to be much more convenient and effective than the conventional angle cleaving method.

1. Introduction

Air-core photonic bandgap fibers (PBFs) have attracted significant interest in recent years because they have lower nonlinear coefficients, lower Rayleigh scattering, and much better adaptability to temperature and radiation than silica fibers [1]. These beneficial features make PBFs a perfect choice for some fiber-optical sensors such as fiber-optical gyroscopes [2]. Backreflection from the fiber termination has a poor effect on the system performance in conventional fiber-optical interference systems because backreflection-induced secondary waves might interfere with primary waves or other secondary waves. This interference often causes increased noise, bias instability, or other deleterious effects.

In fiber-optical systems based on PBFs, backreflection from the fiber termination is expected to be much smaller when the PBF is terminated in air (free end) because most of the light is confined and propagates in the air core [1,3]. Refs. [4,5] theoretically determined and analyzed the reflectivity of the fundamental air-guided mode and bulk modes for flat terminations in an air-core PBF. Kim et al. [6] found the total back-reflected power from PBF was 85% smaller than that from the solid-core SM fiber, but the specific reflectivity for each mode was not clear. Hansen et al. [7] attempted to use an optical time-domain reflectometer (OTDR) to measure the reflectivity for each mode, but no backreflection was observed from the fiber end due to insufficient sensitivity and spatial resolution of the OTDR. In this study, we report the qualitative measurement results of the reflectivity for all of the modes at air-core PBF terminations, including flat and angle-cleaved terminations in air (free end), using the M^2 interferometer.

2. Measurement of backreflection at the termination of PBFs

The M^2 interferometer is a type of time-domain interferometer that can measure distributed backscatter and backreflection of an air-core PBF with a spatial resolution of ~37 µm and a sensitivity of about −140 dB [8]. The basic architecture and operating principle of the M^2 interferometer has been reported in our study [8]. However, the measurement range of the previously reported interferometer is too small (~16.8 cm in air) to be suitable for the present application. Therefore, we first extend its measurement range with a range-extended module, as illustrated in Fig. 1. Light from an amplified spontaneous emission (ASE) source is launched into a single-mode (SM) coupler, which has a splitting ratio of 99:1. In the signal arm, 99% of the light power from the coupler enters the PBF through SM circulator A. The reflected light wave W_S travels backward from the PBF termination and enters an integrated optic chip (IOC) and detector through circulator A. In the reference arm, 1% of the light from the coupler is launched toward the fiber mirror through circulator B, a fiber delay line and a 1×8 optical switch. The reference light wave W_R reflects from the fiber mirror and enters the IOC and the detector. The intensity of W_S can be resolved from the interference signal between W_S and W_R through the lock-in amplifier based on a coherence detection scheme [8].

The fiber delay line is used to change the optical path of W_R to make W_R interfere with W_S, but the fiber delay line has an optical delay range of only 560 ps, so the measurement range of the basic architecture is only ~16.8 cm [8]. At this point, we extend its operation range with a 1×8 optical switch. As shown in the shaded area in Fig. 1, the length

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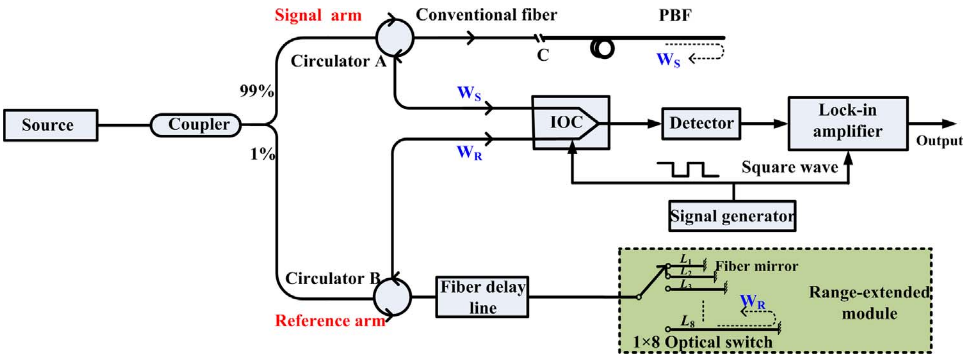

Fig. 1. The M2 interferometer with measurement range extended to ~1.3 m using a range-extended module.

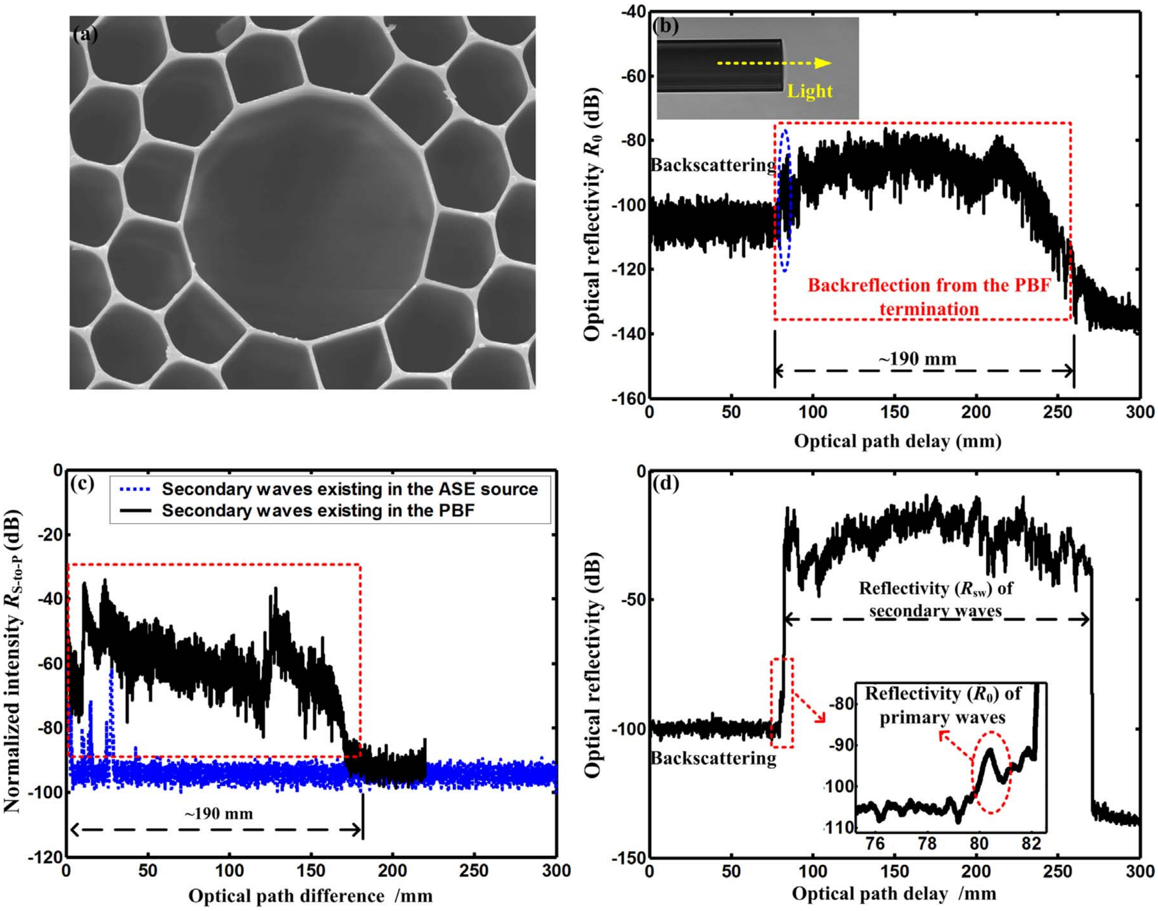

Fig. 2. (a) Cross section of the PBF. (b) Experimental results for the ratio (R_0) of the backscattered and reflected light intensity to the primary waves' intensity after smoothing of 100 times. The inset shows the flat termination of the PBF. (c) Test results of secondary waves existing in the ASE source (blue) and PBF (black) with white light interferometer. (d) Reflectivity of the primary waves and secondary waves in the PBF. The reflectivity of the primary waves is defined as the ratio of the reflected to the incident intensity of the primary waves, and the reflectivity of the secondary waves is R_{sw} that is defined as the ratio of the reflected to the incident intensity of the secondary waves. The inset shows reflectivity of the primary waves. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

difference (ΔL) between any adjacent two fiber arms of the 1×8 optical switch is ~11.5 cm, which corresponds to ~16.8 cm in air, that is, $L_{i+1}-L_i$=11.5 cm (i=1, 2, 3...7). Furthermore, the end of each arm is connected with a polished optical fiber connector because the endface of the polished optical fiber connector generates ~4% reflection and can be used as the fiber mirror in this situation. Therefore, through sequential choice of the eight arms of the optical switch, the optical path of the reference light wave W_R can have a maximum change of $8\Delta L$=~1.3 m (in air). Thus, the M^2 interferometer operation range is extended to ~1.3 m (in air), which is sufficient for the present application.

The experimental setup based on Fig. 1 was established to measure the backreflection at the flat terminations of a 7-cell air-core PBF (Fig. 2(a)) that has a length of ~1.2 m. The PBF has a conventional single-mode fiber (SMF) pigtail, and the fibers are connected using an 8° angle-cleaved fusion splicing to suppress the reflection and avoid saturating the detector [9]. The test results of the backscattering and backreflection for the PBF are given in Fig. 2(b). Before the red rectangle in Fig. 2(b), the curve reveals the backscattering of the PBF; After the red rectangle, there is not any effective reflected signal in this region. Within the red rectangle, the reflection at the flat termination of the PBF is revealed. Obviously, the reflection at the termination of the PBF is not a single peak as would appear for conventional SMF [10]. The reflection starts from the exact endface of the PBF (see the