Mach–Zehnder interferometer formed in a photonic crystal fiber based on a pair of long-period fiber gratings

Jong H. Lim, Hyun S. Jang, and Kyung S. Lee
School of Information and Communications Engineering, SungKyunKwan University, Suwon 440-746, Korea

Jin C. Kim and Byeong H. Lee
Department of Information and Communications, Kwangju Institute of Science and Technology, Oryong-dong, Buk-gu, Gwangju 500-712, Korea

Received August 28, 2003

We demonstrate implementation of an all-fiber Mach–Zehnder interferometer formed in a photonic crystal fiber (PCF). We formed the all-PCF Mach–Zehnder interferometer by mechanically inducing two identical long-period fiber gratings (LPGs) in the PCF. The spectral properties of a LPG and a LPG pair were investigated. The interference fringe formed within the stop band of the LPG pair varied with the period and the strength of the gratings, and the fringe spacing was decreased with increasing grating separation. From the fringe spacing measurement the differential effective group index of the PCF was calculated to be \( m = 2.8 \times 10^{-3} \). © 2004 Optical Society of America

OCIS codes: 060.0060, 060.2340, 230.0230, 350.2770.

Because of the unique guiding and dispersive properties of photonic crystal fibers (PCFs), a PCF consisting of a pure-silica rod with many periodically spaced airholes in the cladding region has attracted considerable attention. Possible applications of PCF are unlimited, and a number of them have been demonstrated. They include dispersion compensation, single-mode operation, PCF lasers, and photonic crystal grating filters. To our best knowledge, no all-PCF Mach–Zehnder interferometers have yet been reported, although many investigators have already demonstrated all-fiber Mach–Zehnder interferometers based on long-period fiber grating (LPG) pairs formed in conventional single-mode fibers. This is so because it is difficult to form two identical 3-dB LPGs in a PCF, unlike those in conventional single-mode fibers for the Mach–Zehnder interferometer.

We report an all-PCF Mach–Zehnder interferometer based on a pair of 3-dB PCF LPGs. We fabricated the LPGs in a PCF by inducing periodic mechanical pressure along the PCF. The characteristics of the all-PCF Mach–Zehnder interferometer are presented. For a pair of LPGs to function as an ideal Mach–Zehnder interferometer in a PCF, half of the LP\(_{01}\) core mode should be coupled to a cladding mode at the first grating and half of the cladding mode should be coupled back to the core mode at the second grating. Thus, for the all-PCF Mach–Zehnder interferometer, one has to form two 3-dB LPGs with identical transmission spectra. However, one cannot generally form a grating in a PCF by exposing the PCF to UV light, because a PCF composed of pure silica, unlike conventional Ge-doped single-mode fibers, in which UV-induced fiber gratings have been widely fabricated, has no photosensitivity. Moreover, it is hard to form the two identical 3-dB LPGs in a PCF for an all-PCF interferometer. For these reasons, it is thought, no one has yet demonstrated an all-PCF Mach–Zehnder interferometer.

We recently developed an all-fiber Mach–Zehnder interferometer by mechanically inducing a LPG pair in a single-mode fiber. Using the same technique, we then formed a LPG pair in a PCF to make an all-PCF Mach–Zehnder interferometer, as shown in Fig. 1. The PCF was fabricated by the stack-and-draw process. A photograph of the cleaved end of the PCF is shown in Fig. 2(a). The PCF consists of a pure-silica core with a diameter of 15 \( \mu \)m and many airholes. The spacing between airholes is approximately 10 \( \mu \)m, and the diameter of an airhole is \( \sim 5 \mu m \). We formed the LPG pairs by pressing the PCF with two identical 2-cm-long groove plates that had a periodicity of 600 \( \mu \)m on a flat plate. Periodic pressure \( P \) on the fiber surface induces periodic index changes in the fiber. The efficiency of the mode coupling between the LP\(_{01}\) core mode and a cladding mode varies with pressure. Grating period \( \Lambda _g \) was selected such that mode coupling occurs at the predetermined wavelength (\( \sim 1550 \) nm) of \( \lambda = \lambda _g (n _{01} - n _d) \), where \( n _{01} \) and...
Fig. 2. Transmission spectra of (a) a single LPG formed in an acrylate-coated PCF \((L = 20 \text{ mm}, \Lambda_p = 600 \mu\text{m})\). Inset, cleaved end of the PCF. (b) All-PCF Mach–Zehnder interferometer consisting of two LPGs \((d = 5.5 \text{ cm})\).

\(n_{cl}\) are the effective indices of the fundamental core mode and the cladding mode, respectively.

The effective index, the grating strength, the grating period, and the resonant wavelength of the pressure-induced LPG can be adjusted, so one can easily form two identical grating pairs in most kinds of fiber, including a PCF. However, this type of LPG formed with periodic pressure possesses linear birefringence with two birefringent axes, parallel to and perpendicular to the direction of the pressure. This birefringence phenomenon happens even with the UV-induced fiber gratings because of strong absorption at the UV-illuminating side of the fiber core. However, the birefringence is not strong enough to induce the 3-dB strength LPG that is necessary for forming a fiber interferometer.

Figures 2(a) and 3(a) show the transmission spectra of the LPGs formed in the PCF with and without the original acrylate coating on the cladding surface, respectively. We launched linearly polarized light by using a single-mode fiber polarizer along the fast birefringent axis to optimize the performance of the interferometer. This polarizer was spliced to the PCF by a mechanical splicer. The splicing loss was \(-6 \text{ dB}\). If the light polarized along the slow birefringent axis is launched, one can measure slightly different transmission spectra owing to the pressure-induced birefringence. The spectral dips indicate resonant mode coupling from the \(LP_{01}\) mode to a cladding mode of the PCF. It is interesting that the single resonant dip in Fig. 2(a) measured with the acrylate coating was split into two dips as in Fig. 3(a) when it was measured after the coating was removed. The phenomenon of resonant dip splitting might originate from the dispersion property of the fiber.\(^{12,13}\) Thus it can be said that the modal index of the PCF cladding mode is affected by the boundary condition of the PCF surface and that the PCF cladding mode is highly dispersive as the higher-order cladding mode of a conventional single-mode fiber. The resonant wavelength of the gratings varied a bit with the location of the gratings owing to fiber irregularity.

For the LPG pair experiment we formed two identical 3-dB gratings. Separation \(d\) between the first and the second LPGs was \(-5.5 \text{ cm}\). The spectrum of the LPG pair measured with the acrylate coating on the cladding surface is shown in Fig. 2(b). Within the stop band of the single LPG we can see several interference fringes. The fringe spacing was measured to be \(-14.1 \text{ nm}\) near the center of the resonant dip. From the measurement, we calculated the differential effective group index of the PCF to be \(\Delta n = 2.8 \times 10^{-3}\) by using the well-known theory.\(^{7}\) The same measurement was then made with the same PCF after the coating had been removed, and the transmission spectrum is depicted in Fig. 3(b). The interference fringe spacing was \(-13.6 \text{ nm}\). And the fringe contrast was
appreciably improved, implying that the cladding mode is easily affected by the existence of the coating.

The transmission spectra of Mach–Zehnder interferometers with different grating separations were also measured. Interference fringe spacing $S$ relative to grating separation $d$ was measured and is depicted in Fig. 4. The solid curve in the figure is the best fit to the equation $S = \lambda^2/(\Delta m d)$. Note that the fringe spacing of the all-PCF interferometer decreases with increasing grating separation, as predicted.

Mach–Zehnder interferometers made from conventional single-mode fibers have been widely studied. As a mode passing through one arm of the interferometer, the cladding mode of the single-mode fiber is completely understood. However, for a PCF the cladding mode is not well defined, because guided-mode formation in the cladding of the PCF has not yet been fully studied. Moreover, the cladding mode might be affected by the airhole distribution far from the core region as well. Therefore the LPG pair in the PCF is considered helpful for studying the mechanism for formation and the properties of the cladding modes guided along the PCF. In our study we found that the cladding mode of the PCF is guided along the fiber and is affected by the condition of the fiber's surface. But understanding the cladding mode of the PCF thoroughly will require further study.

We have described an all-fiber Mach–Zehnder interferometer formed in a photonic crystal fiber. We implemented the interferometer by fabricating two identical long-period fiber gratings in the PCF. We formed the LPGs by pressing a PCF with grooved plates onto a flat plate. The transmission spectrum had one broadband resonant dip when a single LPG was formed in a PCF that had the original acrylate coating. However, after the coating was removed, the resonant dip of the same LPG was split into two dips. The LPG pair fabricated in the PCF showed interference fringes, as in the case of conventional single-mode fiber. The fringe spacing decreased with increasing grating separation. From the fringe spacing measurement the differential group index of the PCF was calculated to be $\Delta m \approx 2.8 \times 10^{-3}$. Although there are still some difficulties in making practical PCF devices, all-PCF Mach–Zehnder interferometers would be promising for use as sensing and communication devices. By analyzing the interference fringe of the LPG pair, one might investigate the mechanism for formation and the spectral properties of the cladding mode of a PCF.

This research was supported by grant R01-2000-00251 from the Korea Science & Engineering Foundation. K. S. Lee’s e-mail address is kslee@skku.ac.kr.

References