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Tunable mode converter using electromagnet-induced long-period grating in two-mode fiber

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ABSTRACT

We present an in-fiber mode converter that changes the propagation ratio of two core modes. A dynamic long-period grating is constructed in a two-mode fiber by the combination of an electromagnet with a nonmagnetic spring coiled around a stiff iron rod. The fundamental mode is converted to the LP_{11} mode according to the voltage applied on the electromagnet. The mode-conversion wavelength can be tuned by stretching the coil spring. Compared to the coupling result with leaky cladding modes, the mode-conversion bandwidth expands from 5 nm to 90 nm and the drive voltage decreases almost by half.

1. Introduction

In-fiber mode converters are promising devices that are used for mode-division multiplexing (MDM) systems, dispersion compensators, variable optical attenuators, and fiber-optics sensors [1–5]. Several techniques, such as multimode interferometers, tapered fibers, and long-period fiber gratings (LPFGs), are used for converting distinct core modes in a few-mode fiber (FMF) [2,5–7]. The LPFG is one of the simplest tools to attain the mode conversion due to its design flexibility and low backward noise. The application of LPFGs is mostly based on the mode transfer from the core-guided mode to the radiation modes at phase-matching wavelengths [8]. By replacing a single-mode fiber (SMF) with the FMF, the LPFG makes a role as a core-to-core mode converter [3,7,9]. In order to vary the spectral characteristics, several techniques have been proposed, which include stretching, bending, and heating of the fibers [4,10,11]. However, the need of machinery to manipulate the fiber may complicate the system and the thermal methods are limited in changing the conversion efficiency without moving the phase-matching wavelength. Recently, we reported a method to change the loss amplitude of the LPFG using an electromagnet [12]. The device configuration is applicable for any fibers and can be formed at arbitrary positions in fiber systems. However, in this experiment, we attached a permanent magnet onto a steel coil spring in order to magnetize the spring since the electromagnet itself hardly induced an attractive force enough to bend the fiber. Therefore the coil spring could not be uniformly stretched since the coil spring was stuck by the permanent magnet. We have thus examined different-pitched coil springs without expansion. Besides, the inversion of magnetic field was required to the electromagnet for initializing the microbend due to the attraction between the magnetized spring and the iron core of the electromagnet.

In this article, we demonstrate the LP_{01}–LP_{11} core mode conversion in a two-mode fiber (TMF) by driving the electromagnet with a nonmagnetic spring coiled around a stiff iron rod. We present the device configuration that can press the spring uniformly to the fiber with the electromagnet and at the same time can uniformly stretch the coil spring.

2. Variable microbend in TMF

Squeezing the fiber by the coil spring creates a periodic asymmetric distortion to the core-to-cladding boundary, *i.e.*, periodic microbend [13]. Such perturbation enhances the mode coupling between the LP_{01} core mode and the LP_{1m} modes that have the same azimuthal dependence of the distorted index distribution at the core-to-cladding boundary [14]. In the TMF, two modes (LP_{01} and LP_{11}) are supported as the propagation modes and while other $LP_{1\mu}$ ($\mu \geqslant 2$) modes are classified as leaky cladding modes under the condition that the refractive index of the outer coating is higher than that of the cladding layer. There are two necessary conditions for the grating-assisted resonance, *i.e.*, phase matching and non-zero electric-field overlap integral. The former is satisfied at the phase-matching wavelengths of $\lambda_p = (n_{01} - n_{1m})\Lambda$, where n_{01} and n_{1m} are the effective refractive indices of the fundamental mode

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and higher order modes, respectively. The latter depends on the modal field distributions over the core-to-cladding boundary and determines the coupling efficiency. Thus the coupling strength can be controlled by tuning the microbend depth. The TMF used here had a step-index profile with a core diameter of 11 μm and a numerical aperture of 0.117. Thus the normalized frequency of the fiber is calculated to be ~2.61 at the wavelength of 1550 nm, which means that it supports only two linear polarized modes. Fig. 1 shows the calculated results of the electric-field distributions of the fundamental mode and the LP_{1m} modes in the TMF. Since the fundamental mode in the TMF matches closely with that of the standard SMF, e.g., Corning SMF28e+, we estimate that the insertion loss will be negligibly low. The electric field of the LP_{11} core mode substantially overlaps with the core-to-cladding boundary, which makes the coupling efficiency higher than that of the cladding modes. We calculated the phase-matching conditions of the LP_{11} core mode and the other higher-order (LP_{12}, LP_{13}, LP_{14}) modes. The phase-matching conditions are shown in Fig. 2 by the grating period as a function of phase-matching wavelength. The refractive indices of the core, the cladding, and the coating layers and their linearly-approximated dispersion $dn/d\lambda$ were deduced from Refs. [15,16]. It is noted that the phase-matching curve of the core-to-core mode coupling is much gradual compared to the core-to-cladding mode coupling. It is attributed that the two guided modes have similar dispersion curves, which results in broad phase-matching bandwidth and high sensitivity to the grating period.

3. Principle of operation

The device configuration of the electromagnet-induced LPFG (E-LPFG) is shown in Fig. 3. The TMF and the coil spring are put in a U-shaped spring holder that is set on the electromagnet. We measured the distribution of magnetic attractive force (MAF) along the spring holder by using a steel ring attached on a digital force gauge. The cylindrical electromagnet having an outer diameter of 90 mm was driven at a voltage rating of 90 V. As shown in Fig. 4, the distribution of the MAF was nonuniform that depended on the positions of the iron core and the yoke of the electromagnet. The MAF was maximized at the both ends of the electromagnet iron core. This result agrees to the theory in which the flux distribution of the electromagnet exhibits an edge enhancement effect [17]. We then inserted the iron rod inside the coil spring to produce the MAF from the electromagnet. Because of high stiffness of the iron rod, the TMF can be uniformly pressed by the coil spring in spite of the nonuniform distribution of the MAF. In this way, the

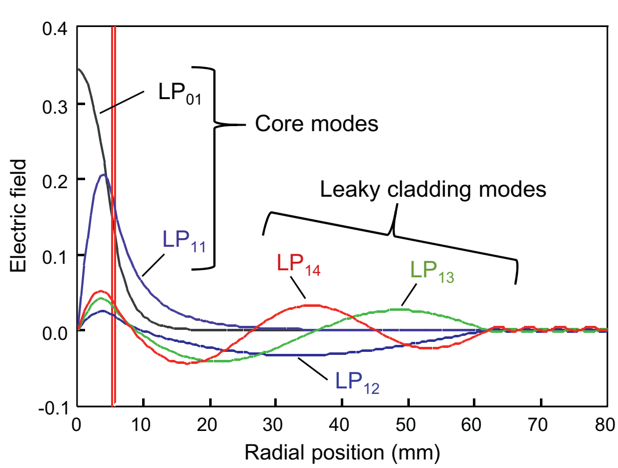

Fig. 1. Electric field distributions in the TMF: The double lines denote the boundary of the core to the cladding layer.

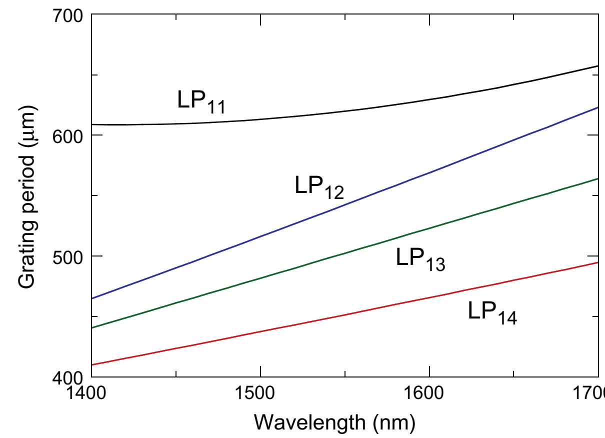

Fig. 2. Phase-matching relations for the coupling of the fundamental mode with the LP_{11} core mode and with the $LP_{1\mu}$ leaky cladding modes.

microbend depth can be uniformly controlled over the fiber by the electromagnet and the coil spring can be uniformly stretched by pulling from both sides.

The measurement setup for evaluating the propagation modes after passing the E-LPFG is also shown in Fig. 3. We transmitted the laser light through a mode stripper to strip out the LP_{11} mode and to ensure the LP_{01} mode input to the E-LPFG. Near-field patterns (NFPs) at the fiber output facet were measured by an objective lens and an infrared camera (Hamamatsu Photonics, C2741-03). The oscillation wavelength of a tunable laser source (Koshin Kogaku, LS-201A) was set at 1550 nm. We expanded the coil spring having a wire diameter of 0.55 mm to set the coil pitch of 620 μm. Fig. 5 shows the behavior of the core mode transition by increasing the voltage applied to the electromagnet. When the electromagnet is off, the NFP shows the LP_{01} mode transmission. By turning on the electromagnet, the microbend grating appears and the mode conversion begins. When the voltage was set to 30 V, the superposition of the two modes was observed. As shown in Fig. 5(c), the applied voltage of 50 V was enough to convert the LP_{01} mode into the LP_{11} mode.

4. Experimental results

When we evaluated the wavelength dependence of the conversion efficiency, a white light source (Ocean Optics, LS-1) was used instead of the tunable laser source and the output light of the E-LPFG was measured by an optical spectrum analyzer (Agilent, 70952A) as shown in Fig. 3. In this measurement, the input and output sections of the E-LPFG were coiled up to ensure pure LP_{01} launch and detection. The iron rod inside the spring was 100 mm long that determined the grating length. The coil spring used here had 161 wires for the length of 100 mm, and the grating period was measured to 620 μm. As shown in Fig. 6, the transmitted power of the LP_{01} mode became attenuated with the voltage greater than 10 V and was reduced by half at ~30 V. The maximum attenuation was obtained at 50 V. The full width at half maximum (FWHM) bandwidth was measured by 90 nm around the center wavelength of 1550 nm. Fig. 7 shows the variation of the loss amplitude of the LP_{01} mode at $\lambda = 1550$ nm with respect to the applied voltage. The loss amplitude increased to 10.4 dB according to the voltage up to 50 V. When the voltage was set beyond 50 V, the loss amplitude became to decrease due to the reverse coupling to the LP_{01} mode. The mode conversion rate lowered at the voltages higher than 70 V. It would be considered that greater pressure is required to compress the acrylic coating as the microbend depth