All-Fiber Add–Drop Wavelength-Division Multiplexer Based on Intermodal Coupling

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***Abstract*—We demonstrate a novel all-fiber add–drop multiplexer by using a tilted Bragg grating written on a two-mode fiber and a mode-selective coupler. The device can be made potentially with low loss and low cost, useful for add–drop of a small number of channels in wavelength-division-multiplexing (WDM) communication systems.**

***Index Terms*—Gratings, optical fiber communication, optical fiber devices, optical fiber filters, wavelength division multiplexing.**

AN OPTICAL add–drop multiplexer (ADM) is a key device in wavelength-division-multiplexing (WDM) communication systems. An ADM with an all-fiber structure is attractive particularly in adding and dropping a small number of wavelength channels since it is relatively easy to achieve desirable features such as low insertion loss and low cost, compared to integrated-optic or hybrid components. Fiber Bragg gratings (FBGs) have been main building blocks for all-fiber ADMs, with advantages of low loss and excellent and controllable spectral shapes. The FBG is then combined with a Mach–Zehnder interferometer [1], grating assisted couplers [2], [3], or other routing components [4]–[6] for the add–drop function. In this paper, we demonstrate a novel all-fiber ADM based on a tilted FBG in a two-mode fiber (TMF) [7] and mode-selective couplers (MSCs) [8]. Unlike previously demonstrated devices, the device presented in this paper is based on coupling between two spatial modes in the TMF. Since the FBG is written on a standard TMF, instead of special section of fibers [2], [6], the spectral shape can be further improved by standard chirping and apodization techniques. Part of the data in this paper has been presented in OFC '99 [9].

Fig. 1 shows the schematic of the ADM. The device comprises two MSCs and a tilted FBG written in a TMF. The TMF is a fiber designed to guide two spatial modes, the LP_{01} and the LP_{11} modes. The MSC is a fiber directional coupler made of a pair of a SMF and a TMF. The two fibers are phase-matched, i.e., the fundamental LP_{01} mode in the SMF and the second order LP_{11} mode in the TMF have the same effective index: the same phase matching condition as in conventional couplers. Therefore, 100% coupling can take place between the two modes, while little coupling occurs between the fundamental modes. The tilted FBG in the TMF reflects light at a specific wavelength band and, at the same time, changes the mode between the LP_{01} and LP_{11} modes [7]. The operating principle of the ADM is as follows. When wavelength-multiplexed optical signals enter the SMF of the first MSC through the input port, the MSC couples all the light in the input SMF into the LP_{11} mode in the TMF. Then the tilted FBG reflects a particular wavelength channel corresponding to its resonant wavelength. At the same time, because of the tilt in the grating, the reflected light changes its mode from the LP_{11} mode to the LP_{01} mode. The reflected light then passes through the MSC without coupling and comes out of the device at the drop port. The other wavelength channels transmit through the FBG without the mode change and are directed to the output port by the second MSC. In the case of the "add" operation, the added signal in the LP_{01} mode is reflected and converted to the LP_{11} mode by the tilted FBG and then it is again directed to the output port.

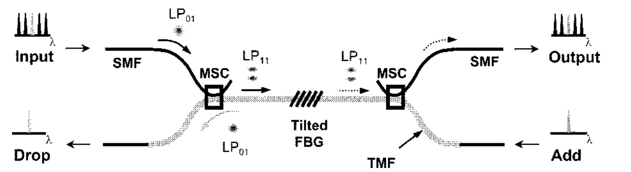

Fig. 1. Schematic of add–drop multiplexer. SMF, single-mode fiber; TMF, two-mode fiber; FBG, fiber Bragg grating; MSC, mode-selective coupler.

The add–drop wavelength is determined by the Bragg condition of the grating

$$\beta_{01}(\lambda) + \beta_{11}(\lambda) = 2\pi/\Lambda$$

where β_{01} and β_{11} are propagation constants of the LP_{01} and LP_{11} modes in the TMF, respectively, and Λ is the pitch of the tilted grating. The reflectivity of a tilted FBG can be estimated by the coupled mode theory [10]. The coupling coefficient κ is given by

$$\kappa = \frac{k}{2} \int \Delta n(x, y)\psi_i(x, y)\psi_j^*(x, y)\, dx\, dy$$

where $\Delta n(x, y)$ is the index modulation of the grating and contains the phase information given by the angle and the orientation of the tilt, and ψ_i and ψ_j are the normalized optical fields of the mode i and j, respectively. κ is related to the peak reflectivity $R_{\max}$ as $R_{\max} = \tanh^2(\kappa L)$ where L is the grating length. For simplicity, we consider a circular-core TMF with NA 0.13 and a core diameter of 12 μm. Since there are two modes, we can think of three mode conversions on reflection: 1) between the LP_{01} and the LP_{01} modes; 2) between the LP_{11} and the LP_{11} modes; and 3) between the LP_{01} and the LP_{11} modes. We assume that the tilt angle is aligned to the lobe orientation of the LP_{11} mode (y-axis), and the refractive index change is present

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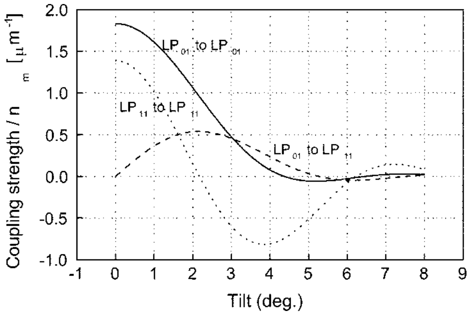

Fig. 2. Calculated coupling strengths of a tilted fiber Bragg grating in a circular core two-mode fiber.

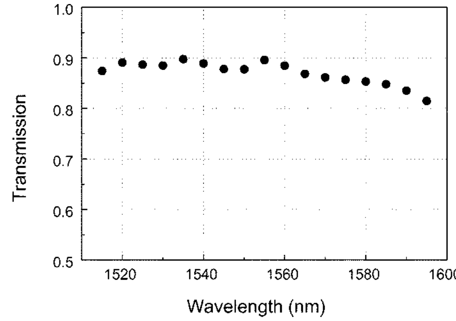

Fig. 3. Coupling efficiency of the mode-selective coupler.

only in the core and uniform, i.e.,

$$\Delta n(x, y) = n_m \cos \frac{2\pi}{\Lambda} (z + y \tan\theta)$$

where n_m is the amplitude of the index modulation, Λ is the grating pitch, and θ is the tilt angle. Fig. 2 shows the calculated coupling strengths normalized by n_m as a function of the tilt angle. In the device configuration shown in Fig. 1, the coupling coefficient between the LP_{11} and LP_{01} modes should be high so as to the corresponding reflectivity is close to 1, while the reflection between the LP_{11} and LP_{11} modes should be as close to zero. It should be noted that the coupling from LP_{01} to LP_{01} is less important here because the LP_{01} mode is not excited into the FBG. Fig. 2 shows that the optimum tilt angle is approximately 2.1°, where the LP_{11}-to-LP_{11} reflection is zero while the LP_{11}-to-LP_{01} reflection is close to maximum. The TMF used in the experiment was an elliptical-core fiber (core size 12 μm $\times 8$ μm and NA 0.13). However, it turned out experimentally that the actual TMF showed similar dependence on the tilt angle as predicted by the above calculation.

Since the core is not circular, the LP_{11} mode has significant nondegeneracy between the even LP_{11} mode and the odd LP_{11} mode corresponding to the lobe orientation with respect to the core axis. The elliptical TMF has an advantage since the lobe orientation of the LP_{11} mode can be maintained over a long length. We fabricated a polished-type MSC with the TMF and one of conventional telecommunication single-mode fibers (SMFs) available in our laboratory. The SMF was chosen since it has the same effective index as the even LP11 mode within a difference of 10^{-4}. The measured coupling efficiency of the MSC is shown in Fig. 3. For the test, we launched a broadband light to the SMF and then measured the optical power coupled to the TMF by using a power meter. The transmission was 90% at the maximum and over 85% in the wavelength range of 1510–1580 nm. However, it turned out that 5% of the light coupled to the TMF was in the LP_{01} mode and odd LP_{11} mode. The unwanted coupling eventually contributes to the loss of the ADM. The loss includes both the insertion loss and the loss due to the finite coupling ratio. The mode extinction ratio, the power ratio of the unwanted LP_{01} mode to the total coupled light, was -20 dB. The extinction ratio is reasonable for a given small index difference between the LP_{01} and LP_{11} mode of the TMF ($\Delta n \sim 0.0024$) and the mode overlap between the LP01 modes of the SMF and TMF. It is expected that the extinction can be improved to -30 dB by a higher NA and a near-cutoff fiber [8]. The polarization dependent loss was 0.2 dB, mainly due to the birefringence in the even LP_{11} mode.

A tilted FBG with a length of 8 mm was written in the TMF after hydrogen-loading treatment by using a KrF laser and a phase mask. The tilt angle was chosen empirically to be 2.0°, and the orientation of the tilt was aligned to the major axis of the core to minimize coupling to the odd LP_{11} mode. The amplitude of index modulation was estimated to be 6×10^{-4}. Fig. 4 shows the transmission spectra of the fabricated FBG when the input signal was either (a) the LP_{01} mode or (b) the LP_{11} mode. In the measurement of Fig. 4(b), the LP_{01} mode is suppressed below -30 dB. The two main notches of similar depths shown in Fig. 4(a) correspond to the LP_{01}-to-LP_{11} reflection at 1555.7 nm and the LP_{01}-to-LP_{01} reflection at 1556.9 nm, respectively. The relative magnitude of the two notches is different from that of Fig. 2, which is believed to be mainly due to the approximation—circular core and uniform grating—in the calculation. The main notch appearing at 1555.7 nm in Fig. 4(b) corresponds to the LP_{11}-to-LP_{01} reflection. The small peak at 1554.6 nm is due to the LP_{11}-to-LP_{11} reflection which we intended to eliminate as much as possible by choosing the tilt angle. The other notches appearing below 1553.5 nm are attributed to the reflection from the LP_{11} mode to cladding modes. (The notches below 1554.5 nm in Fig. 4(a) are also due to the reflection to cladding modes.) Those notches are just loss in the device, but there are a number of known ways to reduce the coupling with cladding modes [11], [12].

The tilted FBG and two MSCs were fabricated in one strand of the TMF. To characterize the performances of the ADM, we launched a broadband light into the input port, and then measured the output spectra both at the drop port and at the output port. The spectrum of the dropped signal is shown in Fig. 5(a). The add–drop wavelength in our device is 1555.7 nm where the LP_{01}-to-LP_{11} reflection occurs. The 3-dB bandwidth of the dropped spectrum was 0.5 nm as determined by the FBG. The optical loss of the dropped signal was 1.5 dB, including the splice loss of 0.5 dB between the TMF and the lead SMF. The center wavelength was insensitive to the input polarization state. However, the polarization dependent loss (PDL) was 0.2 dB, due to the PDL of the MSC. The small sideband peaks at 1554.6 nm and 1556.6 nm correspond to LP_{11}-to-LP_{11} reflection and LP_{01}-to-LP_{01} reflection, respectively. The output spectrum, shown in Fig. 5(b), was basically the same as the transmission spectrum of the FBG when the input light is in the LP_{11} mode [Fig. 4(b)]. The background loss level in the transmission was 1.4$\sim$2 dB except for the narrow loss peaks associated with coupling to cladding modes.

The 90% coupling efficiency of the MSC is currently limited by the index mismatch between the TMF and SMF. In order to

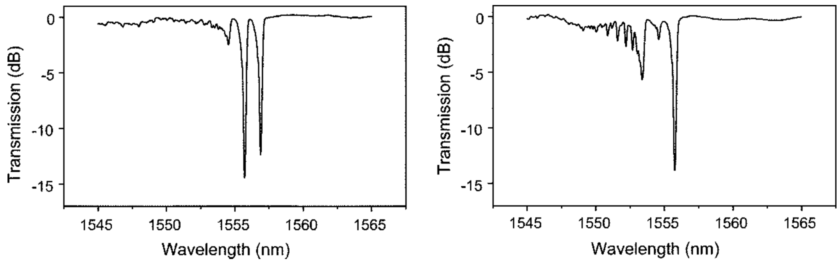

Fig. 4. Transmission spectra of the tilted FBG when the modes of the input are (a) LP01, and (b) LP11.

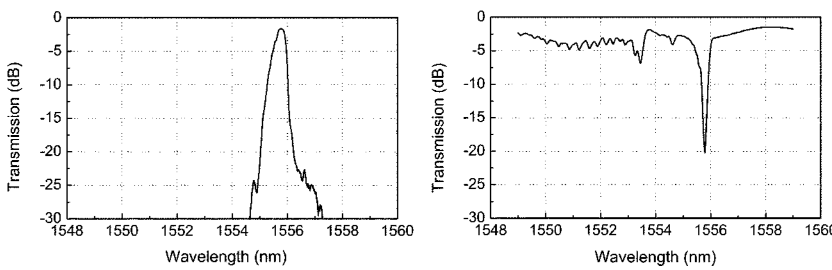

Fig. 5. Performances of the add–drop multiplexer. Transmission spectra at (a) the drop port and (b) the output port.

get a coupling efficiency of 99%, the index difference should be smaller than 5×10^{-5} realistically for a typical effective coupling length of 1 mm. An elliptical-core TMF that has a higher NA and does not guide the odd LP_{11} mode is also desirable since it is easier to suppress the coupling to the LP_{01} and odd LP_{11} modes in the MSC. We recently fabricated a MSC using such a TMF with NA of 0.29 and the cutoff of the odd LP_{11} mode at 1510 nm. The insertion loss and the maximum coupling ratio was 0.5% and 97% respectively, much better than the MSC used in the ADM. We are currently building an ADM using the TMF. Recently, we also demonstrated a fused-type mode-selective coupler that is more compact and stable than polished-type couplers [13].

It is interesting to consider the possibility of exchanging the input port with the drop port, and the output port with the add port. Then, the input signals enter the FBG in the LP_{01} mode. In this case, the tilt angle of the FBG should be adjusted to suppress the LP_{01}-to-LP_{01} reflection. However, the efficiency of the LP_{11}-to-LP_{01} reflection is smaller at the tilt angle where LP_{01}-to-LP_{01} reflection than where LP_{11}-to-LP_{11} reflection is zero, making the original configuration shown in Fig. 1 is preferred.

In summary, we have successfully demonstrated a novel all-fiber add–drop multiplexer using a tilted Bragg grating written on a two-mode fiber and a mode-selective coupler. We expect the performance of the device to be improved by a better adjustment of the tilt angle and a proper two-mode fiber.

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