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Add/drop Filter for CWDM Systems Using Side-coupled Long-period Fiber Gratings

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We demonstrate a simple and effective wavelength-tunable add/drop filter suitable for coarse wavelength division multiplexing (CWDM) systems. The filter consists of two fibers in contact side by side, with identical long-period fiber gratings (LPG) in each fiber. The LPG couples the power in the fundamental core mode to one of the cladding modes, which is then coupled to the same order cladding mode in the other fiber through evanescent-field coupling between two fibers. Finally, the cladding mode in the second fiber is coupled to its core mode with the help of the other LPG. With an optimal longitudinal offset distance of 10 cm, coupling efficiency as high as -1.68 dB and side lobes smaller than -24 dB were experimentally obtained. The experimental results agreed well with the theoretical ones. The operating wavelength of the proposed add/drop filter was tunable by varying the temperature. The temperature sensitivity was measured to be -0.43 nm/°C.

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I. INTRODUCTION

Wavelength division multiplexing (WDM) is one of the important enabling technologies for high-speed communication network systems. This technique allows for many-fold increase in the capacity of existing networks by transmitting many channels simultaneously on a single optical fiber. While dense wavelength division multiplexing (DWDM) is mainly for long haul applications, coarse wavelength division multiplexing (CWDM) is widely used in short- and medium-distance transmission systems and metropolitan networks [1]. Dispersion effect in CWDM systems is smaller, owing to the large channel spacing of about 20 nm, than that in DWDM systems which have channel spacing of 0.8 nm in general. In addition, the system becomes cost effective because precision control of laser temperature is not required. To date, multiplexing/demultiplexing (MUX/DEMUX) components for WDM systems mainly fall into three categories, thin-film interference filters, fiber Bragg gratings, and arrayed waveguide gratings [1-3]. Recently, the use of long-period fiber grating (LPG) has attained considerable interest because of its easy-fabrication, low back-reflection, and good isolation [4-7]. Generally, an LPG is used as a band-rejection filter. It couples the power in the fundamental core mode to various cladding modes at discrete wavelengths [8], which is usually dissipated at the cladding-coating boundary. An LPG coupler, on the other hand, uses the cladding mode for the power coupling between the two fibers. Because it provides both band-rejection and band-pass functions, it can be used as an all-fiber add/drop filter. Such add/drop filters have been demonstrated experimentally, however, the reported coupling efficiencies were too low to be practical [5-7]. Moreover, the incorporation of fused tapered fibers in some designs rendered the fabrication complicated [9]. An LPG band-pass filter consisting of two LPGs fabricated in a single mode fiber with a core mode blocker in between has also been proposed [10]. Although a high transmission of about -0.7 dB at the resonance wavelength has been reported, significant side lobes of -13 dB were generated, which are undesirable in many applications. Thus, it is of practical interest to develop an efficient all-fiber add/drop filter with good channel isolation.

In this paper, we demonstrate a wavelength-tunable add/drop filter for CWDM systems. The filter consists of two single mode fibers placed side by side with identical LPGs in each fiber. The LPG in a fiber couples power from the core mode to the cladding mode in the same fiber, and the coupling between the fibers was made through the evanescent-fields of the cladding modes. To increase the coupling efficiency between the cladding modes, two fibers were twisted slightly against each other with index-matching oil at the interface. Wavelength tuning was obtained by changing the operating temperature of the LPGs.

II. PRINCIPLE OF OPERATION

We consider an add/drop filter composed of two identical single-mode fibers, the transmission fiber and the tapping fiber, each of which contains an LPG, as shown in Fig. 1. The two LPGs are identical with a period Λ and a length d, and offset by a distance s in the direction of wave propagation. Light is launched into the fundamental core mode of the transmission fiber and collected from the tapping fiber. Near the resonance wavelength, the LPG in the transmission fiber couples the light from the core mode to the cladding mode. The cladding mode of the tapping fiber is excited through evanescent-field coupling between the two fibers, and then coupled to the fundamental core mode of the tapping fiber by the LPG in the tapping fiber. To enhance the evanescent-field coupling between the two cladding modes, (i) the fibers are twisted slightly for 2 times over the coupling region for better contact; (ii) an index matching oil having a refractive index similar to the cladding material is applied to relax the confinement of the cladding modes; and (iii) a longitudinal offset is introduced to increase the evanescent-field coupling region. The high sensitivity of LPG to temperature, in general, has been a serious problem in the development of stable LPG-based devices. On the other hand, we can take advantage of the temperature sensitivity to realize a wavelength-tunable add/drop filter.

In our theoretical model, for the sake of simplicity, we assume that the two fibers are parallel and in contact instead of being twisted. The resonance wavelength of an LPG is determined by the phase-matching condition [8]

$$\lambda_m = (n_{eff}^{co} - n_{eff}^{cl,m})\Lambda, \tag{1}$$

where n_{eff}^{co} and $n_{eff}^{cl,m}$ are the effective indices of the fundamental core mode and the cladding mode LP_{0m} (m = 2, 3, 4, ...), respectively. The coupling between the core modes and the LP0m modes of the transmission fiber and the tapping fiber are described by the coupled-mode equations [6], which show that the coupling processes are governed by the grating length, the coupling coefficients of the LPGs, and the coupling coefficient between the two fibers through the LP_{0m} modes. Using the transfer matrix method, the output mode amplitudes of the two fibers can be expressed in terms of the input amplitudes [6]. The coupling efficiency of the add/drop filter is calculated as $\eta = P_{\mathrm{out}}/P_{\mathrm{in}}$, which is a measure of the fractional power coupled to the tapping fiber when light is launched only into the core mode of the transmission fiber. The coupling efficiency η is measured for different offset distance s and compared with the theoretical values.

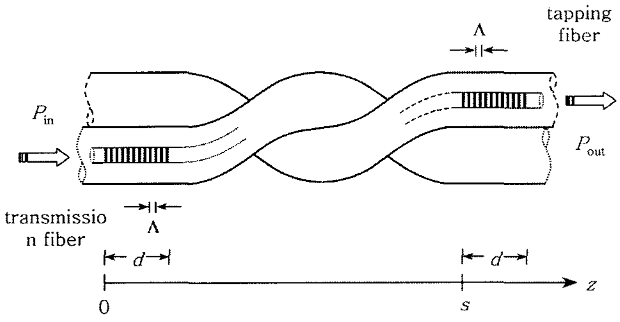

FIG. 1.Schematic diagram of an LPG-assisted add/drop filter, where the fibers are twisted slightly over the coupling region.

Although the transfer matrix method can be employed to numerically evaluate the coupling efficiency for any general case, the method does not give an analytic solution. Therefore, we consider a particular case where the offset distance s is equal to the grating length d, i.e. $s = d$, and the coupling efficiency at the resonance wavelength is equal to 100%. In this case, the coupling efficiency can be expressed in analytical form as a function of wavelength detuning. Interesting things in this particular case are that, at the end of the first LPG, i.e. $z = d$; (i) the power in the core mode of the transmission fiber must go to zero; and (ii) the power must be equally shared by the cladding modes of the two fibers. These lead to two important conditions given by [6]

$$\kappa_{co,cl} = \sqrt{2}\,\kappa_{cl,cl} \tag{2}$$

and

$$d = \frac{1}{\sqrt{3}\,\kappa_{cl,cl}}\left(\frac{2\pi}{3} + 2p\pi\right) \quad \mathrm{p} = 0,\ 1,\ 2,\ ... \tag{3}$$

where $\kappa_{co,cl}$ and $\kappa_{cl,cl}$ are the coupling coefficients for the core-mode/cladding-mode coupling in a fiber and the cladding-mode/cladding-mode coupling between the two fibers for the LP_{0m} mode, respectively. The final coupling varies sinusoidally with the grating length d. Therefore in Eq. (3), to ensure a short grating length, we choose $p = 0$.

When the device satisfies the conditions given by Eqs. (2) and (3), the modal amplitude $A(\delta)$ of the core mode of the tapping fiber at $z = 2d$, which is a function of wavelength detuning δ, is analytically given as

$$\begin{aligned} A(\delta) = \frac{1}{\zeta^2}\Bigg\{ & -\frac{1}{\gamma_{A1}}\exp(j\gamma_{A1}d)\left[\left(\frac{1}{\gamma_{A2}\gamma_{B3}} - \frac{1}{\gamma_{A3}\gamma_{B2}}\right)\kappa_{cl,cl}\chi_1 \right. \\ & \left. + \frac{1}{\kappa_{cl,cl}}\left(\frac{1}{\gamma_{A3}} - \frac{1}{\gamma_{A2}}\right)\chi_2\right] - \frac{1}{\gamma_{A2}}\exp(j\gamma_{A2}d)\left[-\left(\frac{1}{\gamma_{A1}\gamma_{B3}}\right.\right. \\ & \left.\left. - \frac{1}{\gamma_{A3}\gamma_{B1}}\right)\kappa_{cl,cl}\chi_1 - \frac{1}{\kappa_{cl,cl}}\left(\frac{1}{\gamma_{A3}} - \frac{1}{\gamma_{A1}}\right)\chi_2\right] \\ & - \frac{1}{\gamma_{A3}}\exp(j\gamma_{A3}d)\left[\left(\frac{1}{\gamma_{A1}\gamma_{B2}} - \frac{1}{\gamma_{A2}\gamma_{B1}}\right)\kappa_{cl,cl}\chi_1 \right. \\ & \left. + \frac{1}{\kappa_{cl,cl}}\left(\frac{1}{\gamma_{A2}} - \frac{1}{\gamma_{A1}}\right)\chi_2\right]\Bigg\} \end{aligned} \tag{4}$$

with

$$\chi_1(\delta) = \exp(j\gamma_{B1}d)\frac{1}{\gamma_{B1}}\left(\frac{1}{\gamma_{B2}}-\frac{1}{\gamma_{B3}}\right)-\exp(j\gamma_{B1}d)\frac{1}{\gamma_{B1}}\left(\frac{1}{\gamma_{B1}}-\frac{1}{\gamma_{B3}}\right)+\exp(j\gamma_{B1}d)\frac{1}{\gamma_{B3}}\left(\frac{1}{\gamma_{B1}}-\frac{1}{\gamma_{B2}}\right), \quad (5)$$

$$\chi_2(\delta) = \exp(j\gamma_{B1}d)\left(\frac{1}{\gamma_{B2}}-\frac{1}{\gamma_{B3}}\right)-\exp(j\gamma_{B1}d)\left(\frac{1}{\gamma_{B1}}-\frac{1}{\gamma_{B3}}\right)+\exp(j\gamma_{B1}d)\left(\frac{1}{\gamma_{B1}}-\frac{1}{\gamma_{B2}}\right), \quad (6)$$

$$\zeta(\delta) = -\frac{1}{\gamma_{A1}}\left(\frac{1}{\gamma_{B2}}-\frac{1}{\gamma_{B3}}\right)+\frac{1}{\gamma_{A2}}\left(\frac{1}{\gamma_{B1}}-\frac{1}{\gamma_{B3}}\right)+\frac{1}{\gamma_{A3}}\left(\frac{1}{\gamma_{B1}}-\frac{1}{\gamma_{B2}}\right), \quad (7)$$

$$\gamma_{A1} = \frac{2}{3}\left[\sqrt{\delta^2+9\kappa_{cl,cl}^2}\cos\left(\frac{\phi}{3}\right)+\delta\right], \quad (8)$$

$$\gamma_{A2} = \frac{1}{3}\left\{-\sqrt{\delta^2+9\kappa_{cl,cl}^2}\left[\cos\left(\frac{\phi}{3}\right)+\sqrt{3}\sin\left(\frac{\phi}{3}\right)\right]+2\delta\right\}, \quad (9)$$

$$\gamma_{A3} = \frac{1}{3}\left\{-\sqrt{\delta^2+9\kappa_{cl,cl}^2}\left[\cos\left(\frac{\phi}{3}\right)-\sqrt{3}\sin\left(\frac{\phi}{3}\right)\right]+2\delta\right\}, \quad (10)$$

$$\gamma_{Bi} = \gamma_{Ai} - \delta \qquad \mathrm{i} = 1,\ 2,\ 3, \quad (11)$$

$$\cos\phi = -\left(\delta/\sqrt{\delta^2+9\kappa_{cl,cl}^2}\right)^3, \quad (12)$$

where the detuning parameter δ is defined as

$$\delta = \frac{2\pi}{\Lambda}\left(\frac{\lambda_0}{\lambda}-1\right). \quad (13)$$

The normalized output power from the tapping fiber is given by $P_{\mathrm{out}} = |A(\delta)|^2$. It should be noted that these equations hold only for a particular case of two LPGs in series without gap, that is, $s = d$.

III. EXPERIMENTS AND RESULTS

To demonstrate the performance of the proposed tunable add/drop filter, two identical 40 mm-long LPGs with a period of 500 μm were fabricated by exposing Ge-B co-doped photosensitive fibers to 248-nm UV radiation from a KrF excimer laser through an amplitude mask. The UV energy was about 30 mJ/cm^2, with a pulse repetition rate of 30 Hz. The resonance wavelength of each LPG was ~1538 nm, which gave coupling to the LP05 mode. The contrast of the LPGs at the resonance wavelength was about -13.4 dB for an external index of 1.444, which corresponded to $\kappa_{co,cl} \approx 33.9\ \mathrm{m}^{-1}$ 33.9 m^{-1}. Fig. 2 shows how the coupling efficiency at the resonance wavelength λ_m increases with the offset distance s at 24°C. The coupling efficiency reached up to -1.68 dB (68%) with an offset distance of 10 cm. The solid line in the figure is the theoretically simulated curve. In the simulation, the transfer matrix method was used, where the coupling coefficient for the cladding modes was assumed to be 14 m^{-1}. The coupling efficiency reaches a maximum value of -0.5 dB when the longitudinal offset is increased to 10.2 cm, and drops with further increase in the offset distance. Regardless of the assumptions made in our theoretical model, the calculated results agreed well with the experimental results. The slight discrepancy arises from the fact that the coupling coefficient for the cladding modes of the twisted fibers varies with the offset distance, whereas a constant value is assumed in the simulation.

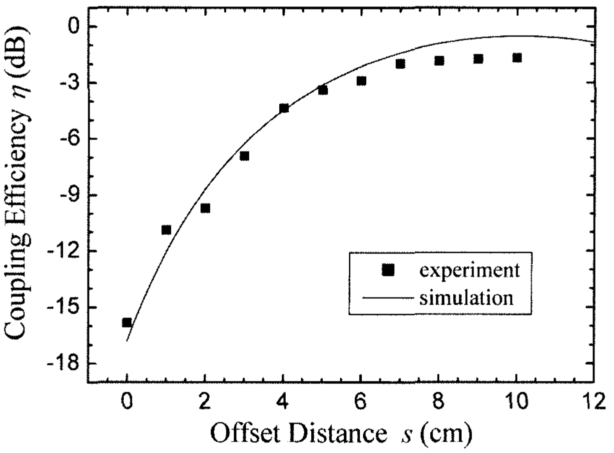

FIG. 2. Variation of the coupling efficiency η at the resonance wavelength λ_m with the offset distance s, showing the achievement of a maximum efficiency when an optimal value of s is used.

The wavelength dependence of the coupling efficiency was measured at 24°C for an offset distance of s = 10 cm and is shown in Fig. 3, together with the transmission spectrum of the transmission fiber. In the figure, we can see that the passing band has a full width at half maximum (FWHM) of ~10 nm. In fact, this bandwidth can be adjusted by the parameter $\lambda_m\Lambda/d$. The spectrum shows a main coupling peak with multiple side lobes located almost symmetrically on both sides of the resonance wavelength. The contrast of the most significant side lobes are about -24 dB. Compared with the published experiments on band-pass filters, constructed by cascading two LPGs in a single mode fiber with a core mode blocker [10] or a hollow optical fiber [11] in between, the proposed add/drop filter produces less significant side lobes. The coupling mechanism involves three processes, the core-mode/cladding-mode coupling in the transmission fiber, the cladding-mode/cladding-mode coupling between the two fibers, and the cladding-mode/core-mode coupling in the tapping fiber. In contrast to the add/drop filter, the band-pass filter utilizes only two coupling processes, the core-mode/cladding-mode and the cladding-mode/

core-mode coupling. The net loss in the transmission spectrum is a product of losses in every coupling process, thus the side lobes in the add/drop filter could be reduced. The transmission spectrum of the add/drop filter obtained from Eq. (4) is shown in shown in Fig. 4, together with the theoretical spectrum of the band-pass filter reported in [10, 11] for comparison. The contrast of the most significant side lobe for the add/drop filter is -21 dB, which is 2.3 dB less than that of the band-pass filter. Further side lobe suppression could be achieved by apodizing the LPGs [12] or/and by adjusting the contact condition between the fibers. The simulated transmission spectrum shown in Fig. 4 has larger side lobes compared to Fig. 3, as it corresponds to the case of strong coupling efficiency with 100% coupling at the resonance wavelength.

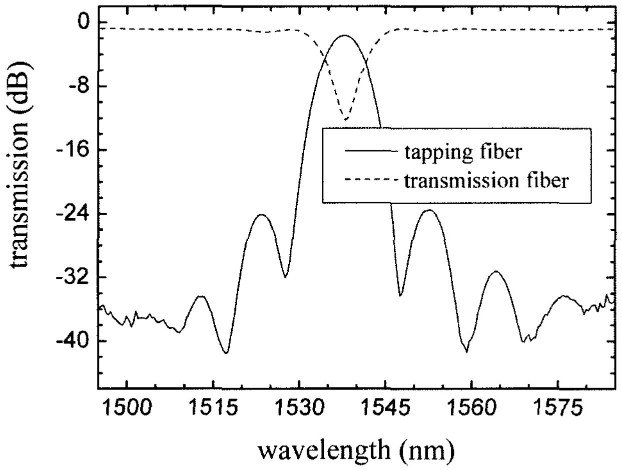

FIG. 3.Measured wavelength dependence of the coupling efficiency for $s = 10$ cm, showing small side lobes located on both sides of the resonance wavelength.

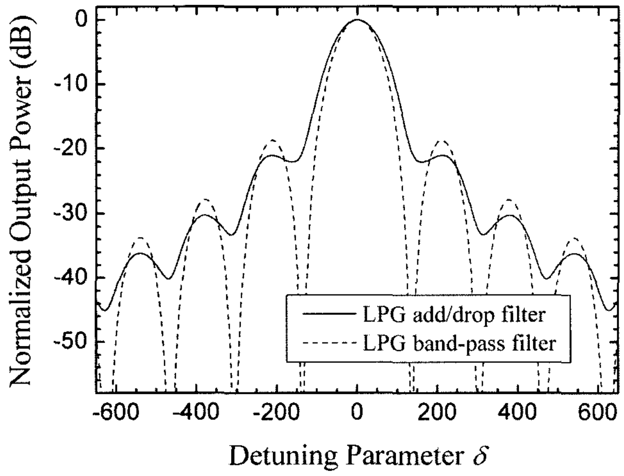

FIG. 4. Variation of the normalized output power of the add/drop filter with the detuning parameter δ. The calculated result for an LPG band-pass filter consists of a core mode blocker (or hollow optical fiber) is also shown for comparison.

It has been widely known that the temperature sensitivity of the resonance wavelength of an LPG depends on the modal dispersion factor and the difference between the thermo-optic coefficients of the core and cladding materials [13]. Hence, the add/drop channels can be tuned by changing the temperature. The measured temperature dependence of the resonance wavelength is shown in Fig. 5. As the temperature was increased from 24°C to 100°C, the resonance wavelength was shifted by about 33 nm, which amounts to a temperature sensitivity of ~-0.43 nm/°C. The wavelength tuning range can be optimized by choosing the cladding mode that has a large modal dispersion factor and/or through the selection of proper fiber materials. LPFGs are attractive alternative for use in CWDM systems as compared to the reported techniques [14-16] due to its easy-fabrication, low cost, and high flexibility in achieving desired spectral characteristics.

IV. CONCLUSION

We have demonstrated a simple and effective LPG-assisted tunable add/drop filter based on evanescent-field coupling between the cladding modes of two fibers. The coupling mechanism is enhanced by slightly twisting the fibers. The coupling efficiency obtained experimentally was as high as -1.68 dB (68%) for a longitudinal offset of 10 cm, which agreed well with the theoretical value of -0.5 dB for an offset of 10.2 cm. Interestingly, the side lobes in the transmission spectrum were suppressed to as small as -24 dB. The resonance wavelength could be tuned linearly with a temperature sensitivity of -0.43 nm/°C. The proposed wavelength-tunable add/drop filters might find potential applications in CWDM systems.

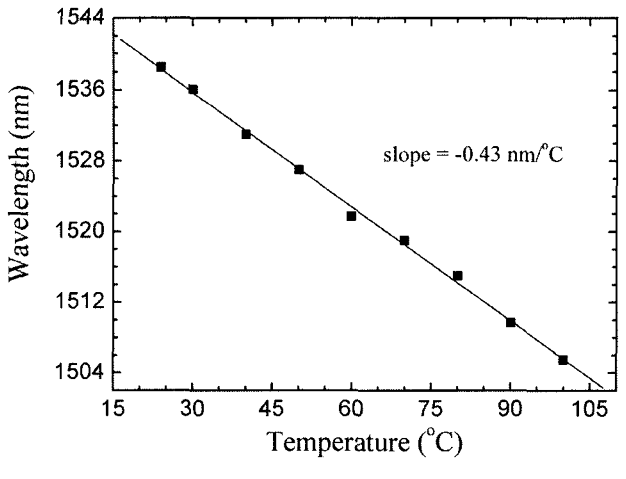

FIG. 5. Measured temperature dependence of the resonance wavelength.

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