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# Channel-selectable multichannel optical add/drop multiplexer based on a sampled fiber grating

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In this paper, we propose and demonstrate a novel channel-selectable multichannel optical add/drop multiplexer consisting of a sampled fiber grating and tunable fiber Bragg gratings. The device adds and drops not only single channel, but also any predetermined multiple channels simultaneously with low interchannel crosstalk by wavelength tuning as small as 0.5 nm or less. The interchannel crosstalk better than 20dB has been shown experimentally.

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## I. INTRODUCTION

Multichannel optical add-drop multiplexers(MOADM's) have become important network components for wavelength division multiplexing(WDM) transmission systems [1]- [3]. Especially, channel-selectable MOADM's, enabling to select either single channel or predetermined multiple channels, play an important role in multiwavelength multichannel lightwave networks. A number of MOADM's have been demonstrated so far [4]- [8]. Among them, the conventional MOADM's [8]- [10] based on a sampled fiber grating(SFG) shown in Fig. 1(a) have many advantages such as low loss, low crosstalk ,compact size and simple structure, because the SFG offers multiple channels with identical wavelength characteristics in a single device. It is difficult, however, for the conventional MOADM's to select any single channel among the multiple channels. Furthermore, the conventional MOADM's cannot drop or add the predetermined multiple channels simultaneously for flexible networking. Recently, a multichannel-selectable ADM has been demonstrated [11] using four identical tunable fiber gratings with the same center wavelength $\lambda_0$. This device is flexible and cost-effective for a WDM system with a small number of channels. But, fast tuning from $\lambda_0$ to $\lambda_1$(1st channel wavelength) through $\lambda_N$(Nth channel wavelength) is difficult when the total number of channels $N$ becomes large.

In this paper, we propose, for the first time, a channel-selectable MOADM with low interchannel crosstalk, consisting of a SFG and tunable FBG's, which can drop or add not only single channel but also any predetermined multiple channels simultaneously much faster than the multi-channel selectable ADM previously reported [11].

## II. PRINCIPLE OF OPERATION

Fig. 1 shows three configurations of the MOADM's with a SFG inserted between two optical circulators(OC's). The SFG is just a grating whose refractive index modulation amplitude and/or phase is itself modulated sinusoidally along the fiber. The channel spacing in the SFG is given by

$$\Delta\lambda = \frac{\lambda_B^2}{2n_{eff}P} \tag{1}$$

where $\lambda_B$, $n_{eff}$ and $P$ are the central Bragg wavelength, the effective refractive index and the sampling period of the grating, respectively. And, the number of channels $N$ is related to the entire grating refractive index profile,

$$n(z) = \Delta n \frac{\sin(N \cdot (L/P) \cdot \pi \cdot (z + P/2L))}{N \cdot \sin((L/P) \cdot \pi \cdot (z + P/2L))}, \quad 0 \leq z \leq 1 \tag{2}$$

where $L$ is the total grating length and $\Delta n$ is the maximum index modulation [9].

When a stream of multiple WDM signals launch into an input port of the conventional MOADM, all the signals described by eqs. (1) and (2) reflect from

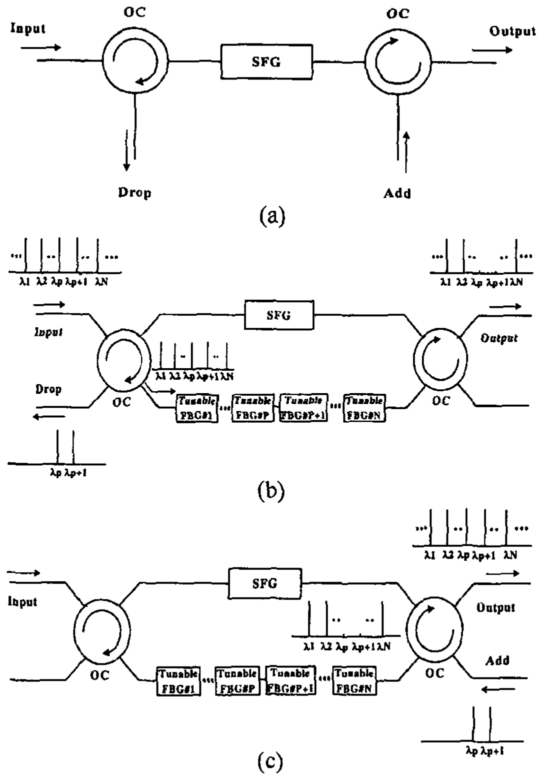

FIG. 1. Three configurations of the MOADM's: (a) a conventional MOADM; (b) the proposed channel-selectable MOADM for a drop operation; and (c) the proposed MOADM for an add operation.

the SFG and drop via the first OC as shown in Fig. 1(a). The other channels pass to the output port via the second OC. Similarly, during the add operation of the conventional MOADM, all the signals specified by eq. (1) and eq. (2) will be added through the second OC.

Figs. 1(b) and (c) show the schematic diagram of the proposed MOADM based on a SFG exhibiting a drop operation and an add operation, respectively. The proposed MOADM consists of a SFG and $N$ number of fiber Bragg gratings(FBG's) to which fiber stretchers or PZT actuators are attached as tuning means. Here, the center wavelengths of the FBG's are allocated between the desired channels and the adjacent ones in WDM signals for easy and fast tunability; i.e. the center wavelength of FBG#1 is set to $\lambda_{\#1} \cong \lambda_1 \pm \Delta\lambda/2$, that of FBG#2 is $\lambda_{\#2} \cong \lambda_2 \pm \Delta\lambda/2$, and so on. Thus, any single or multiple predetermined channels with low interchannel crosstalk can be selected from the WDM signals for the drop/add operation by tuning the FBG's by $\Delta\lambda/2$. In this way, the maximum number of channels to add or drop and the switching speed can be improved from the ADM [11].

In the case of a drop operation, WDM channel signals entering the input port are sent into a SFG via the first OC. Then only the $N$ channel signals among them are reflected by the SFG. The other signals that aren't reflected by the SFG propagate to the output port via the second OC. The $N$ channel signals from the SFG are routed to $N$ tunable fiber Bragg gratings(FBG's) connected in series via the first OC. By tuning the center wavelength(s) of the corresponding FBG('s) to that(those) of all the selected channel(s) to drop, we can drop more than one channel among the $N$ channels simultaneously at the drop port via the first OC. For example, specific channels $\lambda_p$ and $\lambda_{p+1}$ drop at the drop port by adjusting the tuning mechanism(here, fiber stretcher) attached to the corresponding FBG#p and FBG# p+1. The other signals which aren't reflected at the FBG's pass to the output port via the second OC. For an add operation, the channel signals from the add port are reflected by the corresponding FBG's and the SFG, and then are directed to the output port. For example, if we insert the signals $\lambda_p$ and $\lambda_{p+1}$ through the add port, the signals will be added to the stream of WDM signals as shown in Fig. 1(c).

## III. EXPERIMENTS

The experimental setup for testing the performance of the proposed MOADM shown in Fig. 1(b) consists of two 4-port OC's, a SFG and four pieces of tunable FBG's with fiber stretchers. The gratings were fabricated by a 248 nm KrF excimer laser as an UV source. The fiber to be exposed was a standard fiber hydrogen-soaked under the pressure of 100 atm at room temperature for 7 days. A 20 mm-long SFG was written using a 20 mm-long uniform phase mask and a 20 mm-long scatter mask with a period of 540 $\mu$m. The UV exposure time was about 20 min. The scatter mask was formed by inscribing lines periodically onto a fused-silica substrate with a diamond scriber. When UV light strikes into the scatter mask, only light passing thru unetched areas of the mask reaches the fiber, while light impinging on the etched lines is strongly scattered in both transverse dimensions, resulting in only a tiny fraction of this light reaching the fiber core.

The reflection spectra of the 20 mm-long SFG are shown in Fig. 2. The solid lines are the spectra measured by using a broadband LED source and an optical spectrum analyzer(OSA)(resolution 0.08 nm) while the dashed lines are the spectra computed by a transfer matrix method based on the coupled mode theory. Here, the refractive index modulation of $8 \times 10^{-4}$ is assumed. Note that the theoretical curves match reasonably to the measured curves with the channel spacing of 1.5 nm and the channel width(FWHM) of 0.3 nm. The measured spectra show four strong reflection peaks with reflectivity >20 dB at 1536 nm, 1537.5 nm, 1539.0 nm, and 1540.5 nm. The four FBG's, exhibit-

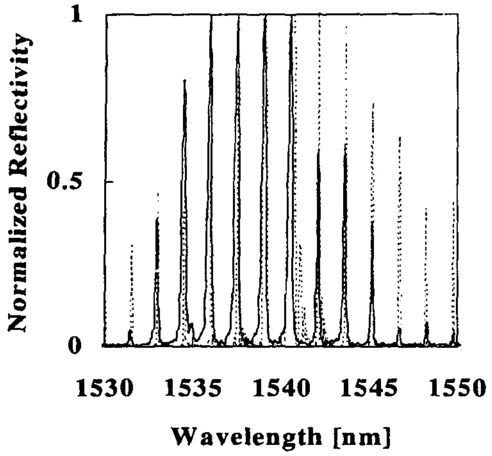

FIG. 2. Reflection spectra of a 20mm-long SFG: solid line (measurement); dashed line (theory).

ing spectral width of 0.4 nm and reflectivity >25 dB, are centered each at 1535.5 nm(FBG#1), 1536.9 nm(FBG#2), 1538.3 nm(FBG#3) and 1539.8 nm(FBG#4), respectively. The wavelength shift per unit microstrain applied by the stretchers was measured to be about 1.1 pm/$\mu\varepsilon$.

To prove the concept of the proposed MOADM, we used the experimental setup illustrated in Fig. 1(b). In the measurement setup, a tunable laser diode generated the channel signals between 1535 nm and 1542 nm, and an OSA analyzed the signal spectra at the drop port. Figs. 3, 4 and 5 show the spectra of the wavelength channels dropped at the drop port for three different cases. Fig. 3 shows a channel dropped by applying a strain to the FBG#2, while Fig. 4 displays two channels dropped by tuning the FBG#3 and FBG#4 simultaneously. Also, Fig. 5 exhibits three channels dropped by adjusting the FBG#1, FBG#3 and FBG#4. The dropped channel signals in Figs. 3, 4 and 5 are mainly dependent on the performance of the used SFG and FBG's. The total insertion loss of the device is less than 3.5 dB and the interchannel crosstalk(or interchannel rejection ratio) is better than 20 dB. These experimental results verify that the proposed MOADM using a SFG and tunable FBG's can add and drop not only a single channel, but also multiple channels with low interchannel crosstalk simultaneously by wavelength tuning less than $\Delta\lambda/2$.

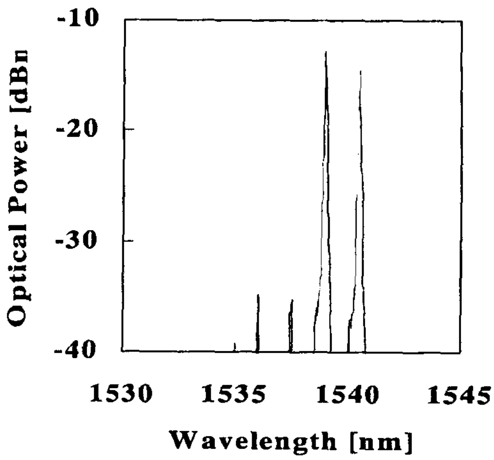

FIG. 4. The signal spectra of two dropped channels at the drop port of a novel channel-selectable MOADM.

## IV. CONCLUSION

We proposed and demonstrated a novel channel-

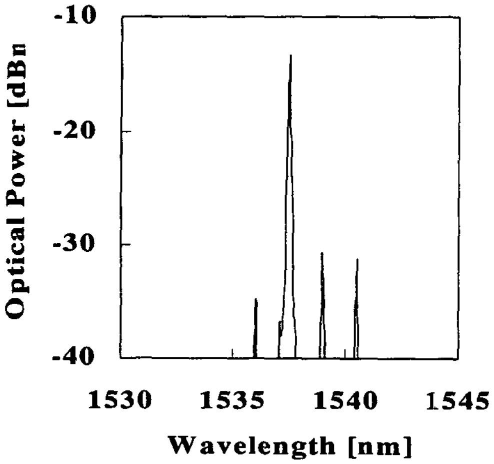

FIG. 3. The signal spectra at the drop port of a novel channel-selectable MOADM for dropping one channel.

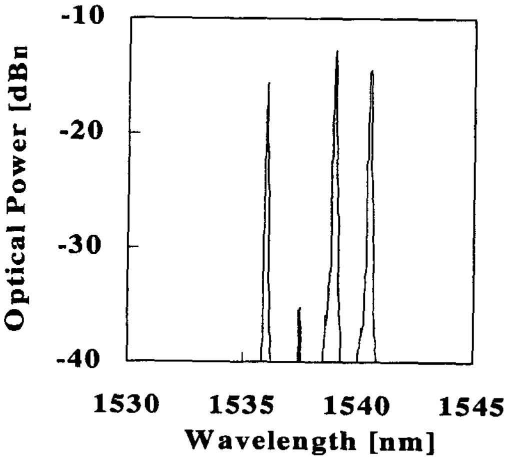

FIG. 5. The power spectra of three dropped signals at the drop port of a novel channel-selectable MOADM.

selectable MOADM with low interchannel crosstalk and potentially fast channel tunability. The proposed MOADM consists of a SFG and tunable FBG's whose center wavelengths are allocated between the desired channels and the adjacent ones. The interchannel crosstalk better than 20 dB has been shown experimentally. The proposed device also demonstrated to drop multiple channels simultaneously with wavelength tuning as small as 0.5 nm or less. The performance of the channel-selectable MOADM including the crosstalk and channel tunability can be further improved by carefully designing the SFG and appropriately allocating the center wavelengths of the FBG's.

## V. ACKNOWLEDGEMENT

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