Add–Drop Multiplexers and Interleavers With Broad-Band Chromatic Dispersion Compensation Based on Purely Phase-Sampled Fiber Gratings

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***Abstract*—We propose an add–drop multiplexer (ADM), designed using a purely phase-sampled superstructure fiber Bragg grating and capable of compensating accumulated link dispersion over a wide bandwidth. Both the grating period and the sampling period are chirped linearly along the length of grating for realizing broad-band compensation. We also discuss how such gratings can be used to design a multichannel ADMs and channel interleavers while compensating the dispersion for all reflected channels.**

***Index Terms*—Add–drop multiplexer (ADM), Bragg gratings, dispersion compensation, dispersion slope compensation, interleaver, optical fiber devices, wavelength-division multiplexing (WDM).**

ADD-DROP multiplexers (ADMs) are used for selective adding and dropping of wavelength channels and constitute a key component for lightwave communication systems making use of dense wavelength-division multiplexing (DWDM). ADMs are especially useful for routing networks or for wavelength-division-multiplexing (WDM) systems designed using a reconfigurable ring topology [1]. The traditional ADM configuration, based on a fiber Bragg grating (FBG) placed between two optical circulators, is simple to implement but suffers from unavoidable optical losses. Devices based on Bragg gratings inscribed in the waist of fused fiber couplers have also been proposed for making a compact ADM [2].

ADMs based on interleaved gratings have been proposed in [3]. In the limit that interleaved sampling is continuous with constant amplitude, one can obtain high reflectivity even with a relatively small index modulation by effectively using grating length. An interleaved sampled grating consists of several different amplitude-sampled gratings with suitable sample and grating periods. Because the differences in Bragg wavelengths (corresponding to grating periods of each amplitude-sampled grating) are larger than the WDM channel bandwidth, spectral characteristic of an interleaved grating can be obtained by just adding the contributions of independent amplitude-sampled gratings. An interleaved grating is not a sampled grating but consists of multiple amplitude-sampled gratings. In this method, the reflectivity outside of stopband cannot remain very low. Moreover, to make the grating, several different phase masks are needed.

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An effective way to decrease the channel spacing, and thus, increase the number of channels, is to interleave channels with wider channel spacing. Interleavers enable the practical implementation of DWDM systems by separating a single set of closely space channels into multiple sets of widely spaced channels (and vice versa). Most interleavers use a cascaded Mach–Zehnder design and are made using planer lightwave circuit technology, a modified Mach–Zehnder interferometer with a ring resonator, thin dielectric films, or arrayed-waveguide gratings. Recently, an optical interleaver based on an amplitude-sampled FBG has also been proposed [4].

In wide-area networks, the management of both the group-velocity dispersion and its slope becomes critical for high-capacity transmission [5], [6]. A single-channel grating device can be designed by solving the layer-peeling method of [7]. The response of a multichannel grating device with identical in-band characteristics also can be obtained by this method. Optimization for multichannel FBGs using three distinct steps has been discussed in [8]. The related problem of finding the phase profile, corresponding to minimal amplitude variations of the sampling, allows the use of semianalytical methods. Recently, we proposed the use of purely phase-sampled FBGs for this purpose [9]. In this letter, we design an ADM using such gratings and show that our proposed ADM not only drops (or adds) a channel but it can also simultaneously compensate the accumulated dispersion for all the remaining channels. Our ADM is made by placing a purely phase-sampled FBG between two optical circulators. We also discuss how such a device can function as a multichannel ADM or a channel interleaver.

Fig. 1 shows schematically the design of the proposed ADM. It consists of two three-port optical circulators and one phase-sampled FBG. The grating is designed such that it reflects all channels of a WDM signal entering from Port 1, and exiting from Port 3, except the channel that need to be dropped. The dropped channel appears at Port 2. The grating can also add the same-wavelength channel when it enters through Port 4. The FBG of Fig. 1 makes use of phase sampling and requires chirping of both the grating and the sampling periods for compensation of dispersion [9]. More specifically, we use a purely phase-sampled superstructure FBG, i.e., the sampling function for the effective mode index is periodic in phase $\phi(z)$, not amplitude. In this case, the required index modulation scales with the number N of channels as $\sqrt{N}$, rather than N, as found in the case of amplitude sampling. The period of the phase-sampling function determines the reflectivity spectrum that is periodic in frequency with channel spacing $\Delta\nu = c/(2n_0\Lambda_s)$, where n_0 is

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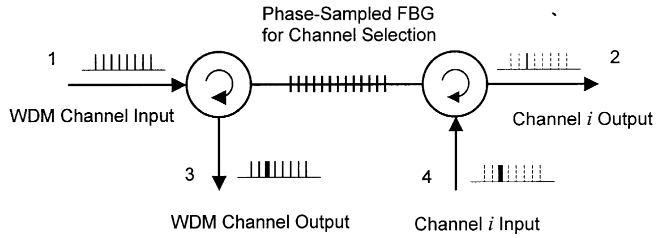

Fig. 1. Schematic of an ADM designed for broad-band dispersion compensation. It consists of two three-port optical circulators and one purely phase-sampled FBG.

the average refractive index, and Λ_s is the period of the sampling function. The actual shape of $\phi(z)$ governs the peak reflectivity R_p for each channel. Our objective is to design the phase profile such that R_p is nearly one for all reflected WDM channels but zero for the channel that needs to be dropped or added.

To design a purely phase-sampled FBG such that R_p is the same for all WDM channels except the add–drop channel, we use a multidimensional minimization algorithm. We divide the sampling period Λ_s into many small segments and choose a trial form of $\phi(z)$. We then calculate the partial reflectivities corresponding to each Fourier coefficient and compute the mean-square deviation from the ideal value. The algorithm changes $\phi(z)$ iteratively to minimize the mean-square deviation [9]. Fig. 2 shows the optimized phase profile obtained using only 20 segments and designed to add–drop the second channel in an eight-channel WDM signal. The coupling coefficients for this phase profile are almost the same for the remaining seven WDM channels.

We show in Fig. 3 the transmittivity (dotted line) and reflectivity (solid line) spectra of the ADM together with the group delay and dispersion at the WDM channel wavelength, all calculated for the phase profile shown in Fig. 2 using a transfer-matrix approach. The grating parameters are chosen to be $L = 10$ cm, $\Delta n_1 = 4 \times 10^{-4}$, and $\Lambda_s = 1$ mm. We chirped the grating period at a rate of $\delta\Lambda_0 = 0.08$ nm/cm. To compensate for the dispersion slope $S = dD/d\lambda$, we introduce a chirp in the sampling period Λ_s as well. The required chirp depends on the value of S of the fiber used in the WDM link and is given by $\delta\Lambda_s = (S/D)\Lambda_s\Delta\lambda_{ch}$, where $\Delta\lambda_{ch}$ is the channel spacing. The sampling period changes by $\delta\Lambda_s/\Lambda_s = 1.7\%$ at the end of the grating in Fig. 3. Note that the delay time for the transmitted channel is nearly constant with wavelength (dashed line) but varies linearly for the reflected channels (solid line). The slope of the delay time is different for different channels and, thus, can be used for compensating dispersion as well as the dispersion slope. In Fig. 3, the dispersion parameter D changes at a constant rate for reflected channels. Such an ADM can compensate the dispersion of all reflected WDM channels (with 100-GHz spacing) over 320 km of Corning LEAF fiber. Furthermore, it can operate for channel bandwidths >0.5 nm.

To reduce the group-delay ripple, apodization over 33% of the total grating length was used. The isolation for ADM was found to be more than 30 dB. In Fig. 3, average reflectivity of reflected channels is 99.96%, and average time-delay ripple is 6.6 ps. When we changed the average reflectivity to 68%, average time-delay ripple was reduced to 2.0 ps. These results for sampled gratings are similar to those found for chirped gratings.

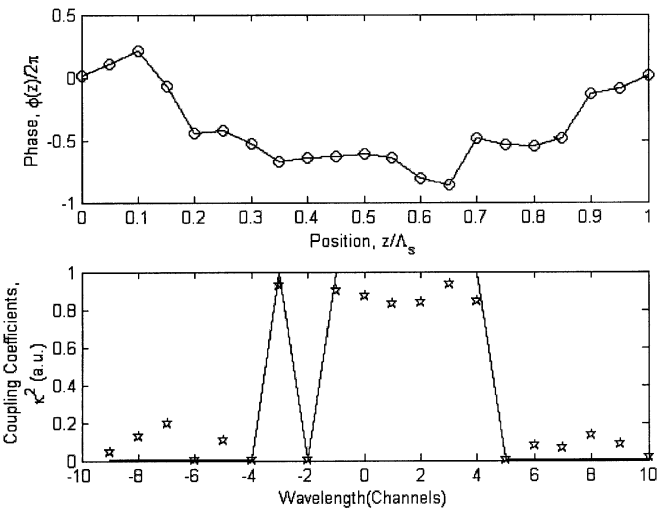

Fig. 2. Optimized phase profile of the ADM designed to drop (and add) Channel 2 in an eight-channel WDM signal. Resulting coupling coefficient is shown in the bottom panel. Stars denote the location of wavelength channels.

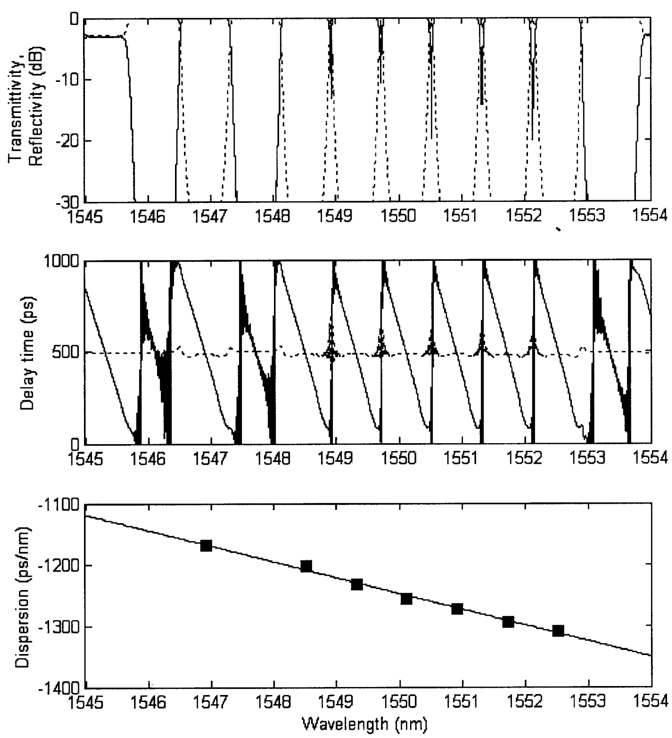

Fig. 3. Transmittivity (dotted line) and reflectivity (solid line) for the phase profile of Fig. 2 (top), resulting group delay (middle), and dispersion D at the WDM channel wavelength (bottom) for the ADM designed to drop a single WDM channel.

The proposed ADM design is versatile enough that it can be used to drop (and add) multiple WDM channels at preset wavelengths. As an example, Fig. 4 shows the case in which the ADM is designed to drop Channels 4 and 11 from a 16-channel WDM signal. The only change occurs in the phase profile $\phi(z)$ associated with each sampling period. The optimum phase profile was found by using 30 segments and is shown in the top panel of Fig. 4. The grating is still 10 cm long but $\Delta n_1 = 5.8 \times 10^{-4}$, $\delta\Lambda_0 = 0.07$ nm/cm, and $\delta\Lambda_s/\Lambda_s = 2.1\%$. The transmission, reflection, and dispersion characteristics for the optimum phase

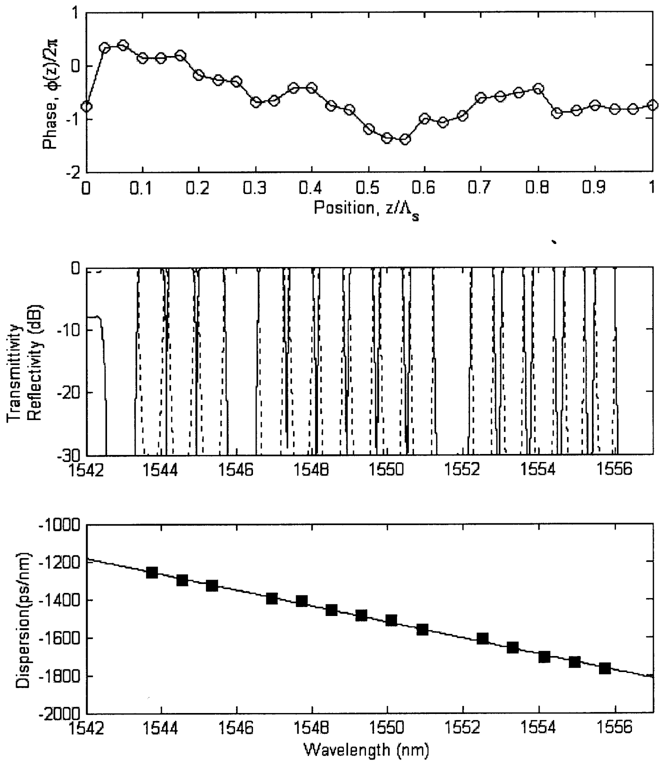

Fig. 4. Optimized phase profile an ADM designed drop (and add) Channels 4 and 11 among the 16 WDM channels. Transmittivity and reflectivity spectra (middle) and dispersion D at the WDM channel wavelength (bottom) are also shown for such a multichannel ADM.

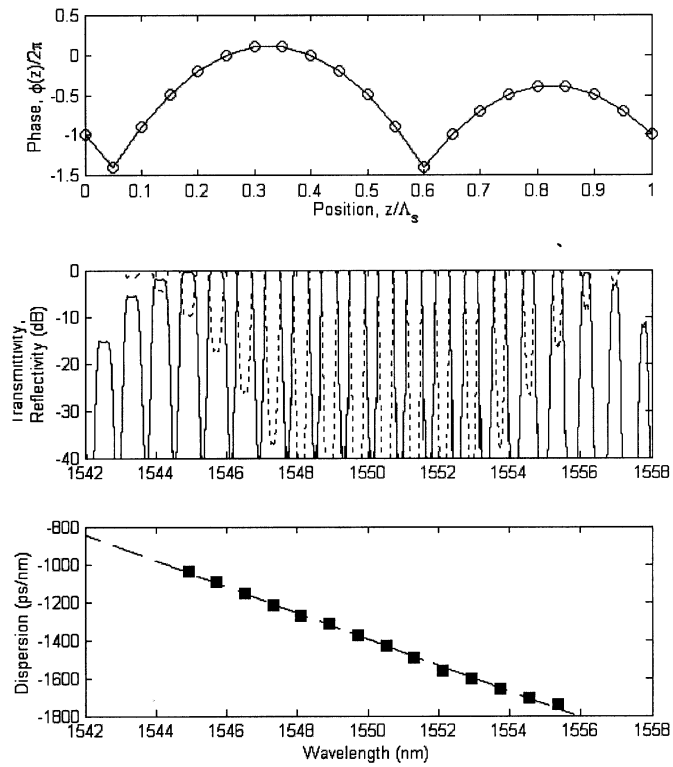

Fig. 5. Same as in Fig. 4 except that the phase-sampled grating is designed to act as a channel interleaver by dropping or adding alternate channels.

profile are also shown in Fig. 4. Again, D changes at a rate of 42 ps/nm^2 that matches the dispersion slope of the fiber.

As a final example, we design a DWDM interleaver that reflects alternating channels while also compensating dispersion for all reflected channels. The top panel in Fig. 5 shows the optimized phase profile for the phase-sampled grating used to make an interleaver. The transmittivity, reflectivity, and dispersion D of the 20-channel interleaver (50-GHz channel spacing) are also shown in Fig. 5. The grating parameters are chosen to be $L = 5$ cm, $\Delta n_1 = 6 \times 10^{-4}$, $\Lambda_s = 2$ mm, $\delta\Lambda_0 = 0.04$ nm/cm, and $\delta\Lambda_s/\Lambda_s = 2\%$. The peak reflectivity is almost one for all even channels but nearly vanishes for all odd-numbered channels. Such a device can compensate dispersion of all reflected WDM channels while separating the odd and even numbered channels. The device also shows low loss and high-extinction ratio. It is possible to increase the number of channels by changing the grating parameters.

In conclusion, we have proposed a new class of ADMs and interleavers based on the use of a purely phase-sampled superstructure FBG, sandwiched between two optical circulators. Both the grating period and the sampling period are chirped linearly along the length of the grating. Such gratings are easier to fabricate than amplitude-sampled gratings because they require much reduced index modulation. They can be designed to compensate dispersion of a large number of WDM channels by adjusting the amplitude of phase modulation and the chirp of sampling function. The proposed device can be used to make multichannel ADMs as well as interleavers while providing dispersion compensation for all reflected channels.

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