Pass Band Broadening in Molded-glass Echelon-grating-based CWDM Filter Module

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Abstract

We have developed an inexpensive WDM (wavelength division multiplexing) filter module by using a molded-glass echelon grating as the key component. This grating is designed to provide the wide transmission pass band (>13 nm) required by a CWDM (coarse WDM) filter. The body of the module and the ferrule that secures the optical fibers are fabricated by injection molding. The volume of the module is approximately $5.5 \times 5.5 \times 28.0$ mm^3, which is almost the same as that of an MU connector. The fabricated CWDM filter module is designed to handle four optical signals whose wavelengths are 1511, 1531, 1551, and 1571 nm. The measured insertion loss and 1-dB-down bandwidth of the module are 5 dB and 13.5 nm, respectively. The crosstalk performance is better than –17 dB. The channel center wavelength is highly stable (within ±0.5 nm) over a wide range of ambient temperature from –40 to +85°C.

1. Introduction

Wavelength division multiplexing (WDM) is a vital technology in optical telecommunications systems. The top of the network hierarchy utilizes narrowly spaced, densely packed WDM called DWDM (dense WDM). However, the use of DWDM is still limited to the top layer because of the very high cost of stabilizing the wavelength of the light that carries signals through the transmission line. The solution to this problem is to use filters that have a wide, flat passband, which enables operation even when the wavelength of the optical signals varies within a certain range of the band. This idea led to CWDM (coarse WDM), which has the potential to decrease system costs by eliminating the expensive wavelength stabilizing techniques.

The most popular optical filters that can meet the requirements for CWDM are dielectric thin film filters. We previously reported the basic characteristics of a filter module employing an injection-molded polymer echelon grating [1]. However, the transmission pass band was too narrow for CWDM because we had not developed the design theory. Recently, we have developed a new optical filter module that uses a press-molded glass echelon grating. This module offers the transmission characteristics required by CWDM filters, such as a wide pass band, symmetric demultiplexing and multiplexing operations, and highly stable operation over a wide range of ambient temperature.

2. Echelon grating filter

2.1 Grating

The principle of the echelon grating filter [2], which was first proposed by A. A. Michelson, can be briefly summarized as follows. The structure consists of a series of optically transparent planes stacked parallel to each other as shown schematically in **Fig. 1**. The length of each plane monotonically decreases or increases with a constant length difference, which leads to interference among transmitted optical waves in the focal plane. In deducing the function describ-

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ing the optical amplitude at the focal plane, let us consider the two adjacent optical paths I-I' and II-II' in Fig. 1. The optical length difference D between the two is expressed as

$$D = l(n - \cos\theta) + d\sin\theta, \tag{1}$$

where l and d are respectively the length difference parallel to and the height difference perpendicular to the optical wave propagation. The angle θ is the diffraction angle, and n is the refractive index of the grating material. Equation (1) can be rewritten to express the amount of phase difference $\Delta\phi$ as

$$\Delta\phi = \frac{2\pi d}{\lambda}\sin\theta + \frac{2\pi l}{\lambda}(n - \cos\theta). \tag{2}$$

Assuming an echelon grating consisting of N steps, we can obtain the optical amplitude in the focal plane by summing the intensity of optical waves passing through each tier. Therefore, the optical amplitude should have the form [3]

$$u(\mathbf{r}) = \sum_{m=1}^{N} E_m(r)\exp[-j\Delta\phi_m(r)], \tag{3}$$

where j is an imaginary unit, $\mathbf{r}$ denotes the position vector that terminates at the point in the focal plane, and $E_m(r)$ and $\Delta\phi_m(r)$ express the absolute value and the phase originating from the partial light that passes through the m-th tier. To make a wide transmission pass band, the parameters d and l must be modified to have the specific values given to the m-th tier. Thus, they should be expressed as d_m and l_m in Eq. (3).

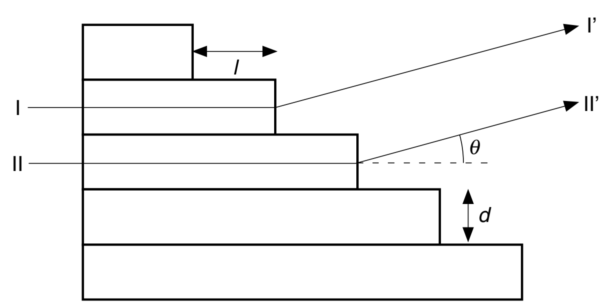

Fig. 1. Schematic illustration of an echelon grating.

2.2 Filter characteristics

The structure of our CWDM filter module is shown schematically in **Fig. 2**. The module basically consists of inlet and outlet optical fibers, a pair of lenses that form the collimated optical system, and the echelon grating. As the module is designed to handle four optical signals having different CWDM-spaced wavelengths, the four outlet fibers are gathered together by a ferrule. In the demodulation (DEMUX) operation, an optical beam comprising four channels of signals/wavelengths is collimated by the first lens and illuminates the echelon grating. The grating demultiplexes the signal into four separate optical signals and focuses them at different positions in the focal plane. Each of the optical fibers receives one of the four optical signals. The multiplexing (MUX) operation is the same in reverse.

The transmission spectral responses of the module can be calculated using Eq. (3). An example of the calculated transmission spectral response of an echelon-grating-based optical filter module is shown in **Fig. 3**. In the calculation, the center wavelengths of the four channels were set to 1511, 1531, 1551, and 1571 nm. The calculated response of the grating, which is intended to provide the basic CWDM characteristics, exhibited 13.5-nm-wide flat transmission (1-dB-down bandwidth) and crosstalk performance of better than –17 dB throughout the band.

3. Experimental results

Figure 4 is a photograph of an assembled CWDM filter module, which is of the inline type. It shows, from the left-hand side, a single inlet optical fiber, a collimating lens, an echelon grating, a condenser lens, and a four-fiber outlet array. The enclosure or the body of the module was fabricated by injection molding and made of a plastic commonly used for ferrules. Thanks to the small size of the grating and the inline arrangement of the module structure, the

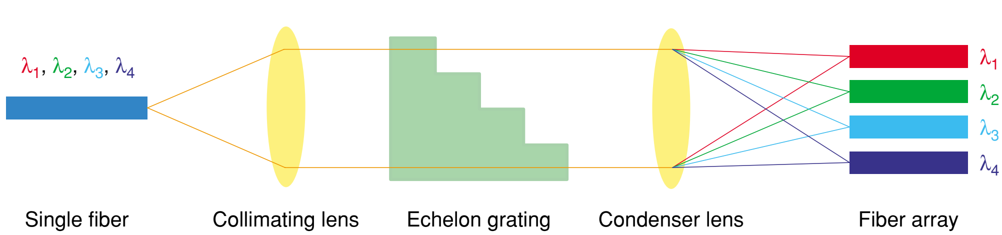

Fig. 2. Basic structure of the echelon-grating-based optical filter module.

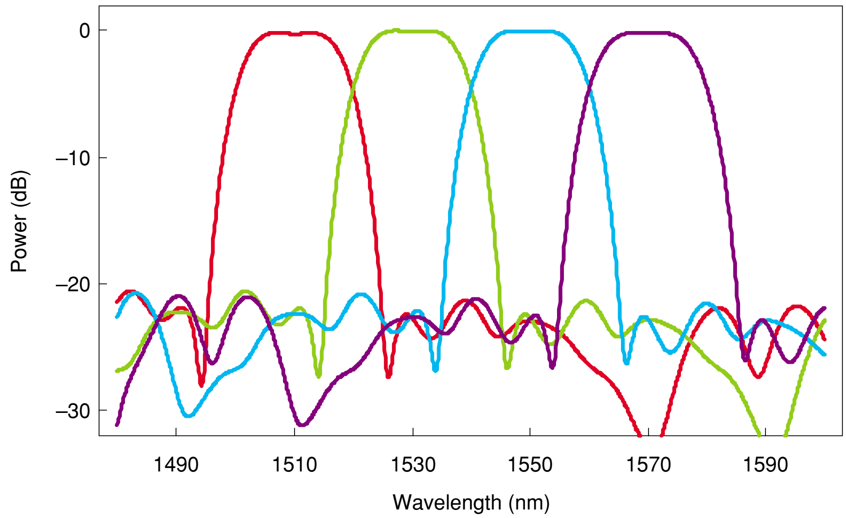

Fig. 3. Calculated transmission spectral response of the filter module.

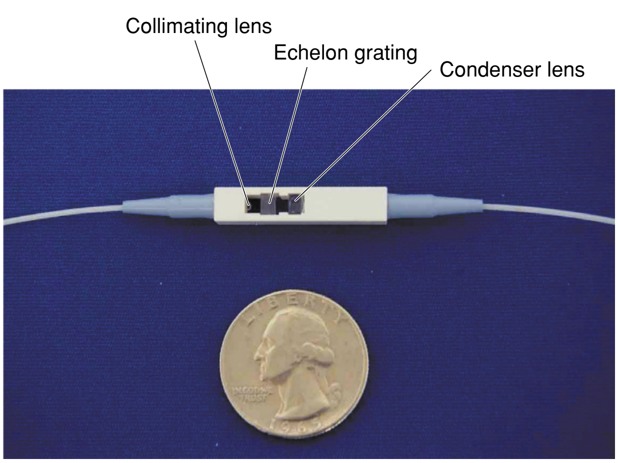

Fig. 4. Photograph of a completed filter module.

volume of the module is only $5.5 \times 5.5 \times 28.0$ mm^3. The volume of the grating is far less than 1 mm^3.

The transmission spectral responses were measured in the wavelength range from 1480 to 1600 nm using a tunable laser source and an optical spectrum analyzer. Assigning the first channel as 1511 nm, we obtained wavelengths of 1531, 1551, and 1571 nm for the second, third, and fourth channels, respectively. The transmission spectral response of the module operating in DEMUX mode is shown in **Fig. 5**. The measured 1-dB-down pass bandwidth and crosstalk were 13.5 nm and –17 dB, respectively. These CWDM characteristics are almost the same as the designed values. At present, the insertion loss of our module is approximately 5.0 dB. The excess loss appearing in the optical connection and the molded-glass echelon grating contribute almost equally to the loss. We think that it should be possible to reduce the insertion loss to well below 3.0 dB by improving the optical connection scheme and the fabrication accuracy of the grating.

Another important characteristic of the optical filter module is stability against variations in environmental conditions, especially temperature. The wavelength of the central channel is plotted against ambient temperature ranging from –40 to +85°C in **Fig. 6**. The wavelength variation was less than ±0.5 nm. This indicates that the module is highly stable over a wide range of ambient temperature.

4. Discussion

Initially, we made an injection-molded polymer echelon grating because injection molding can easily fabricate sophisticated structures such as echelon gratings. However, we should also consider that polymer materials generally have a large temperature dependence in material expansion and/or refractive index. This dependence leads to a large change in the central wavelength of a channel when the ambient temperature changes, which we confirmed experimentally. This weakness makes our first design of echelon grating-based filters unsuitable for CWDM. The most promising solution was to use glass to form the gratings because glass has comparatively low thermal dependences. Thanks to advances in the high precision molding, we were able to overcome the difficulties of forming glass echelon gratings and the fabrication cost was almost the same as that for poly-

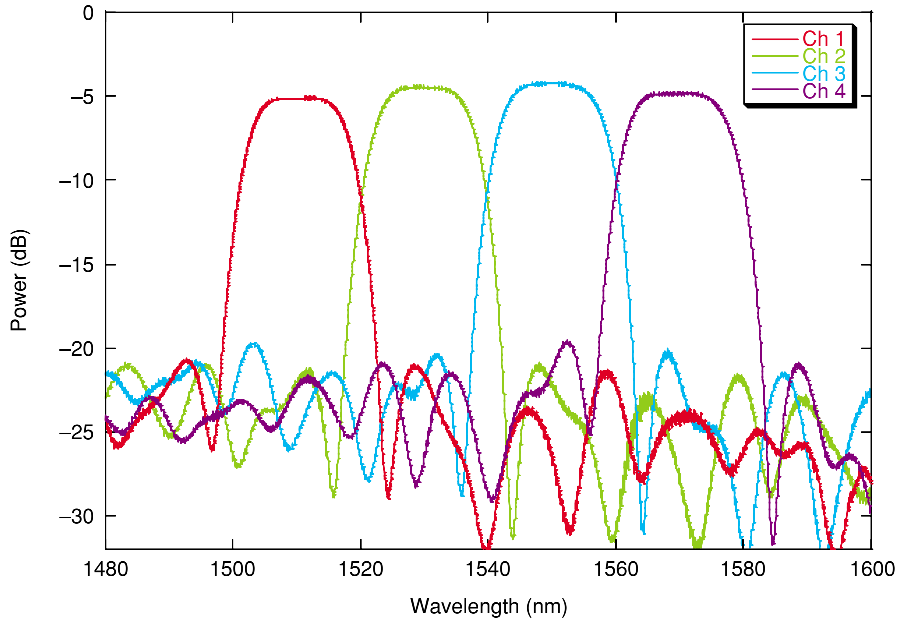

Fig. 5. Example of the measured transmission spectral response.

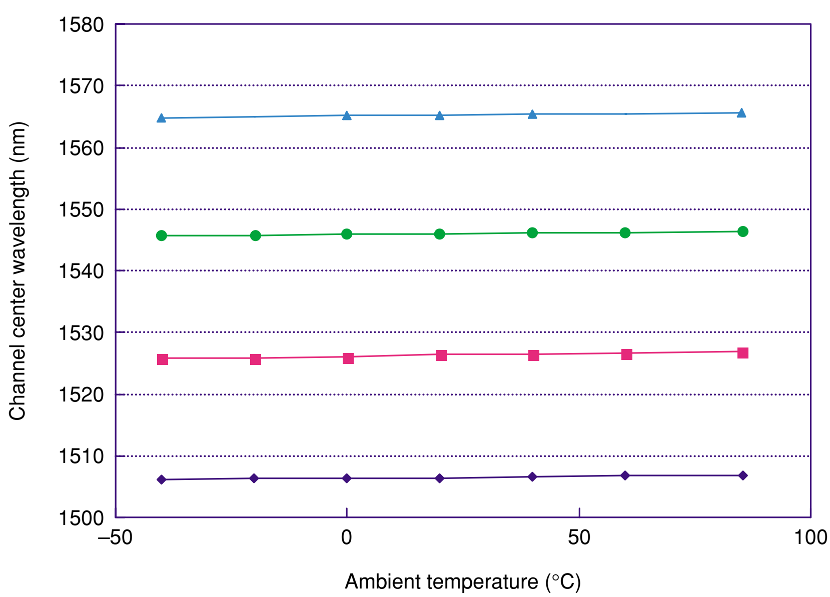

Fig. 6. Relationship between the channel center wavelength and ambient temperature. The variation of the channel center wavelength was less than ±0.5 nm.

mer injection molding.

However, low thermal expansion and optical index change coefficients are not enough to produce highly stable operation over a wide range of ambient temperature. We think our excellent operating characteristics were also aided by other factors: (1) the coaxial arrangement of components along the optical axis, (2) the symmetrical design of the body around the optical axis, and (3) the use of the same materials for the body and the ferrule (plastic) and for the echelon grating and lenses (glass). Although the contribution of each factor to stable operation is not clear at present and should be clarified quantitatively in the near future, these temperature-tolerant transmission characteristics make our molded-glass echelon-grating-based filter highly competitive among commercially available filters.

5. Conclusion

We reported the fabrication and characteristics of a new compact four-channel CWDM filter module employing a molded-glass echelon grating. Press molding and injection molding techniques were used to reduce manufacturing costs. The filter module multiplexes and demultiplexes multiple optical signals using only one echelon grating. The measured pass bandwidth and crosstalk performance were 13.5 nm and –17 dB, which coincide very well with the designed values. The obtained insertion loss was around –5.0 dB, which is somewhat large. However, it will be reduced by improving the optical connection and the fabrication accuracy of the echelon grating. The best feature of the module is its highly stable operation over a wide range of ambient temperature. The characteristic performances of the grating in this module show that the echelon grating is promising for developing low-cost high-performance CWDM filter modules.

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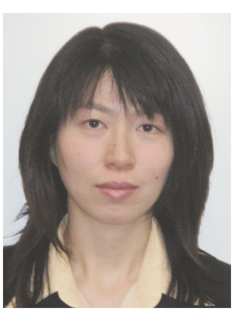

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