Optical-isolator-based modules for monitoring DWDM tunable lasers

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Simultaneous monitoring of power, wavelength, and channel number for a tunable laser is demonstrated by use of a combination of an optical isolator, an etalon, a polarizer, and photodiodes. The mode hopping and incomplete-tuning problems that might arise in tuning the laser can be detected with the proposed approach. The spectral response of the monitoring module can be adjusted to match the wavelength-tuning range. The spectral adjustment can be performed by rotating the input polarization or the output polarizer. It can also be tuned by rotating the second stage if a two-stage isolator is used. We demonstrate experimentally the feasibility of this approach by use of discrete fiber-pigtailed components. © 2004 Optical Society of America

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1. Introduction

Wavelength-division-multiplexed (WDM) networks require performance monitoring of various signal parameters to provide a high quality of service and ensure network survivability. The performance monitors can be placed in the transmitters, intermediate nodes, or receivers. In the intermediate networking nodes the channel number, optical signal-to-noise ratio (OSNR), and other performance parameters need to be monitored [1–4]. We focus on performance monitoring for tunable laser sources (TLSs). The monitored parameters include power, wavelength, and channel number.

TLSs are critical components for dense WDM (DWDM) networks as spare sources or fast wavelength-switching devices. A tunable laser module is usually packaged with an optical isolator to prevent the laser from external optical feedback as well as a Fabry–Perot (FP) etalon to stabilize its wavelength. The wavelength monitor for controlling a tunable laser diode must cope with multiple output wavelengths and the required tuning speed. The tuning curve of a TLS might change due to aging or temperature variation, which can give rise to mode hopping and incomplete-tuning problems in tuning a TLS [5]. The wavelength of a TLS can be locked to a DWDM wavelength grid, specified by the International Telecommunication Union (ITU), by use of an FP etalon [5–8]. However, it is difficult to detect mode hopping and incomplete tuning with a single etalon because of its periodic spectral response. The ambiguity among different channels can be resolved from a channel-dependent characteristic of an optoelectronic component. Many components, such as a dielectric filter [5, 9, 10], an arrayed waveguide grating [2], a Mach–Zehnder interferometer [11], a long-period fiber grating [12], double detectors [13, 14], a semiconductor optoelectronic diode (SOD) [15], and so on, were proposed for monitoring a TLS.

Here we propose to use a combination of an optical isolator, a linear polarizer, and related optical components to monitor the wavelength and channel number of a tunable DWDM laser. Those components can be integrated with the power and wavelength stabilization parts in a compact module. This scheme is advantageous over the existing methods in terms of cost and module size. The polarization of an output signal through a polarization-independent isolator varies with wavelength, so the output is made wavelength dependent by placing a linear polarizer after the isolator. The wavelength dependency can be used for channel recognition. On the other hand, the combination of an isolator and a polarizer functions as a tunable notch filter, which can be used to suppress the signal for measuring the noise power [4]. Thus it can be used to obtain the OSNR, especially for coarse WDM (CWDM) channels.

2. Spectral Response and Tunability

Figure 1 shows the mathematical model for this isolator-based module. Each component in an optical isolator is described with the corresponding Jones matrices [16]. The principle of an isolator typically involves nonreciprocal rotation of the light polarization and rejection of the reflected light by use of a polarizer or polarization beam splitter (PBS). The input light is separated by a PBS into two rays of orthogonal polarizations and passes through a Faraday rotator to achieve isolation for both polarizations. The two rays can have different phase velocities due to the birefringence of the crystal used for the PBS. After combining the two rays at the output stage by use of a polarization beam combiner (PBC), which can also be birefringent, the phase difference between the two rays causes the rotation in the output polarization state. For example, a $LiNbO_3$ wedge can be used as a PBS or PBC [17]. Separation of the polarizations occurs because the birefringent crystal has two indices of refraction, one for the light polarized along the crystal's optical axis and another for the light polarized perpendicular to the optical axis. After a polarization rotation of 45° by the Faraday rotator, the optical axis of the PBC crystal is oriented 45° with respect to the optical axis of the PBS. Thus the ordinary ray of the PBS is also the ordinary ray of the PBC, and the extraordinary ray of the PBS is the extraordinary ray of the PBC. Since the ordinary and extraordinary rays have different indices of refraction, phase difference occurs between the two rays as they travel from the input to the output of the isolator. The birefringence enhances the rotation of the polarization state and causes the output polarization state to be sensitive to the index dispersion of the crystal. This makes the state of polarization of the output light strongly dependent on the wavelength of the input light. It has been demonstrated before that a birefringent plate sandwiched between a polarizer and a polarization analyzer functions as a spectral filter [18]. The use of an isolator instead of a birefringent plate has the additional advantage of immunity to optical reflection, so it can have more flexible applications.

The isolator-based module can allow versatile adjustments on the spectral response for matching of the wavelength-tuning range. The adjustments can be carried out by a variety of changes in the arrangement of the input polarization, output polarizer, and insertion of birefringent components.

2.A. Single-Stage Isolator with a Polarizer

In our analysis the refractive indices of $LiNbO_3$ crystals are used [19]. For the input and output waves with Jones vectors J_1 and J_2, respectively, the channel-monitoring (CM) module, including an output polarizer, can be written in a compact matrix form as

$$J_2 = TJ_1 \,, \tag{1}$$

where

$$T = PL(\theta)\,C(-45°)\,T_2C(45°)\,R(45°)\,T_1 \tag{2}$$

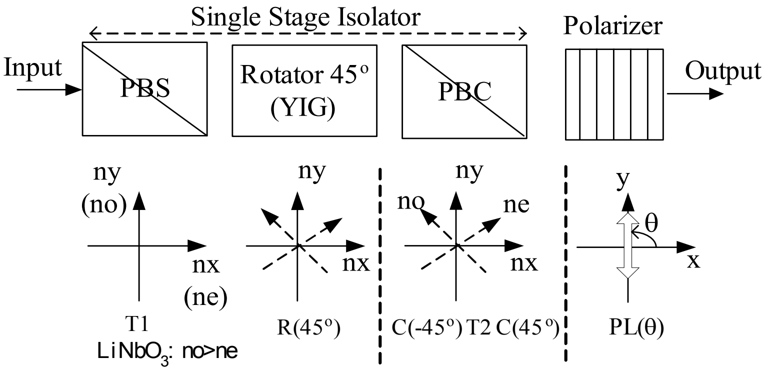


Fig. 1. Model of the isolator-based module with a single-stage polarization-independent optical isolator.

for a single-stage isolator. The system matrix can be simplified as $T = PL(\theta)C(-45°)T_2T_1 = PL(\theta)R(45°)T_2T_1$. The PBS and PBC can be regarded as wave retarders (fast axis along the x direction) and represented by matrices T_1 and T_2, respectively. The polarization rotator rotates the polarization plane of a linearly polarized wave by an angle θ and is represented by matrix $R(\theta)$. Matrix $C(\theta)$ represents coordinate transformation. $PL(\theta)$ stands for a linear polarizer whose transmission axis makes an angle θ with the x axis. The matrix forms of the above components can be found in Ref. [16].

Figure 2 shows the output response for a single-stage optical isolator with a 45° linearly polarized input light and an output polarizer whose angle can be adjusted. The optical path lengths of the PBS and PBC are both assumed to be 0.4 mm. The orientation of the polarizer changes from 0° to 90° with respect to the x axis. It is clear that the output response varies with wavelength and can be tuned by rotating the polarizer. It can also be tuned by rotating the input polarization but fixing the output polarizer. For a fixed input polarization and output polarizer the output response is periodic in wavelength with a free spectral range (FSR). The transmission coefficient of the module can also be shifted in the wavelength domain by inserting a wave plate in front of the polarizer. Figure 3 shows that tuning the spectral response by varying the thickness of the wave plate can give rise to a more uniform characteristic compared with tuning by rotating the input polarization or output polarizer. In the calculation the angle of the polarizer is set at 90°, and the input wave is linearly polarized at 45°. The above analyses show that an isolator-based module can easily be tuned to cover a wide range of wavelengths.

2.B. Two-Stage Isolator with a Polarizer

The FSR of the monitoring module can also be tuned by use of a two-stage isolator, which allows the wavelength sensitivity and monitored wavelength range to be adjusted. The Jones matrix of a two-stage optical isolator is described by

$$T = C(-\phi)R(45°)T_2T_1C(\phi)R(45°)T_2T_1 \,. \tag{3}$$

The second stage is rotated by ϕ with respect to the x axis. We use the same isolator parameters as for the single-stage isolator, except that the optical path length of the second stage is chosen to be 0.6 mm. The output responses for three angles of rotation of the second stage are shown in Fig. 4. The polarizer is oriented at $-45°$, and the input wave is linearly polarized at 45°. The change in the FSR is obvious. Such a change is caused by compensation of the overall birefringence by rotation of the second stage. A larger FSR indicates that

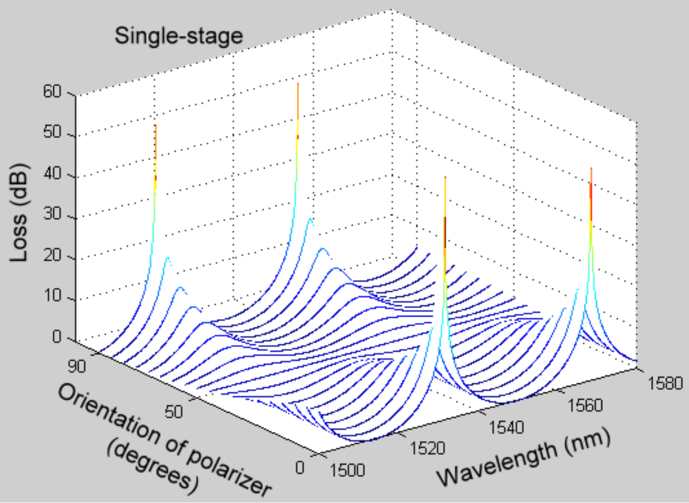


Fig. 2. Output response for a single-stage optical isolator with a 45° linearly polarized input light and an output polarizer whose angle is adjusted.

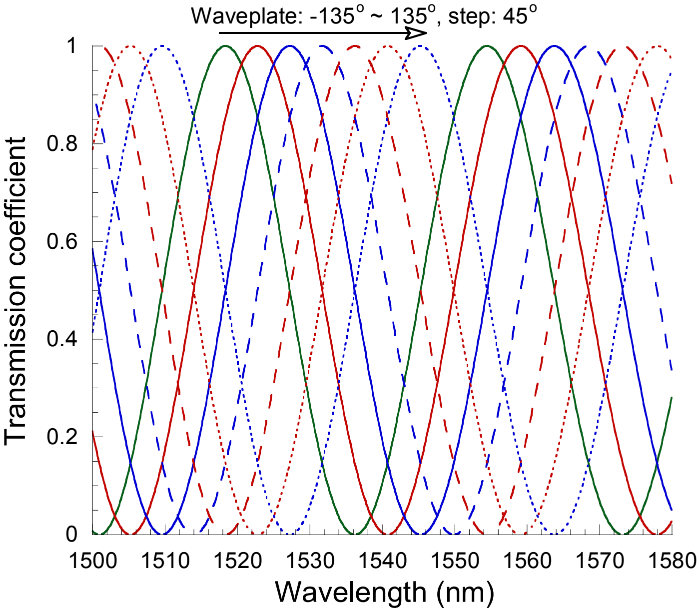


Fig. 3. Spectral tuning by changing the thickness of the wave plate. The corresponding phase retardation due to the thickness change varies from −135° to 135° with a step of 45°.

the phase difference between the two orthogonal polarizations is better compensated. It is possible to completely compensate the phase difference if the two isolators have identical optical path lengths.

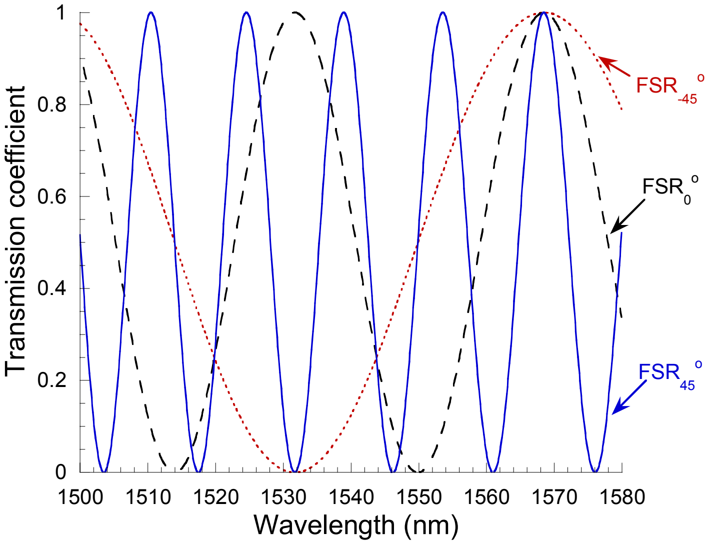


Fig. 4. Spectral tuning by rotating the second stage of a two-stage optical isolator.

The phase difference of an isolator is usually specified by the differential group delay (DGD), and the FSR is related to the DGD value by the following equation[20]:

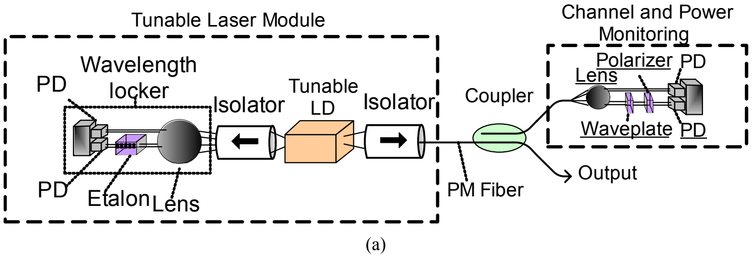
$$\mathrm{FSR}\,(nm) = \frac{7.8\,(ps - nm)}{\Delta\tau\,(ps)}\,, \qquad (4)$$

where $\Delta\tau$ is the DGD value. Therefore, for a required monitoring wavelength range ($\approx \mathrm{FSR}/2$), an isolator with an appropriate DGD value must be selected. The value of $\Delta\tau$ can be simply measured by the fixed analyzer polarization mode dispersion (PMD) measurement method [20]. Typical two-stage optical isolators use birefringent plates to compensate the PMD [21]. For CM a certain amount of PMD is needed to provide the wavelength-dependent characteristics.

3. Tunable Laser Monitoring

Figure 5(a) illustrates the concept of adding a CM path to a DWDM tunable laser that uses an FP etalon for wavelength stabilization. In packaging the isolator with a tunable laser the optical axis of the input PBS must be adjusted to obtain the best spectral response. This can also be achieved by adding a wave plate after the isolator. This scheme is ideal for monitoring edge-emitting lasers since they typically emit linearly polarized light. The wave plate and polarizer can also be packaged with the laser. For direct packaging with the laser we suggest inserting a wave plate of specific thickness to match the monotonic spectral range with the laser tuning range. Although adjusting the orientation of the wave plate can also cause a relative shift in the spectral response, selecting a wave plate with the right thickness can give rise to a more controllable spectral response and allow for simpler packaging. The wave plate can also be properly designed to compensate the thermal drift of the isolator response [10].

The CM function can be integrated with the power-monitoring and wavelength stabilization functions in a compact module, as shown in Fig. 5(b). The isolator can be one-stage



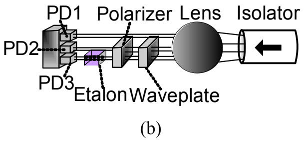


Fig. 5. (a) Schematic of a tunable laser with a wavelength locker and an add-on channel monitor, and (b) a compact module with power-, wavelength-, and channel-monitoring functions.

or two-stage, depending on the laser tuning range and the required flexibility. This module can be placed at one side of the tunable laser such that all the parameters can be monitored with the light output from the same laser facet. This is especially important for monitoring tunable lasers since the powers from two end facets might not follow each other. From Fig. 5(b) one can observe the advantages of using an isolator in the monitoring module. The reflection from the FP etalon and residual reflection from the photodiodes (PDs) can be rejected by the isolator.

The CM path needs a monotonic wavelength response that covers the entire tuning range of the tunable laser. The wavelength range of the monotonic response is roughly equal to half the FSR, which is in turn determined by the phase difference between the two orthogonal rays. Near 1550 nm the FSR of an optical isolator is governed by Eq. (4). One can choose an isolator with an appropriate DGD value to match the monitored band. The isolator used in the experiments has a DGD value of 0.243 ps, so its FSR is 32 nm.

In addition to the power monitoring with photodiode PD1, wavelength locking is performed with the signal ratio of PD3 to PD2, whereas channel recognition is performed with the signal ratio of PD2 to PD1. After wavelength switching, channel recognition is performed after the wavelength is locked to an ITU grid.

To demonstrate the feasibility of the proposed approach, we investigated the monitoring characteristics with discrete components, including an external-cavity tunable laser, a polarization-independent isolator (E-TEK model PIFIA1AP55222), a polarization controller (PC), a linear polarizer, and an FP etalon. The PC is required because of the use of fiber-pigtailed components. It can also help tune the spectral response. Figure 6 shows the response for cascading the isolator, PC, and a polarizer. The monitored wavelength window and the slope of the curves change with the input polarization states of the polarizer. These curves are similar to those shown in Fig. 2. In Fig. 6, PC1–PC5 refer to different input polarization states induced by arbitrary adjustment of the PC. These results demonstrate the tunability of the spectral response of the proposed approach. The PC can be adjusted to generate a steeper spectral response if only a few closely spaced channels are to be monitored. The CM is tunable but has a stable spectral response because the PC (or wave plate) is fixed.

Figure 7(a) shows the spectral responses of PD2 and PD3. The wavelength is locked

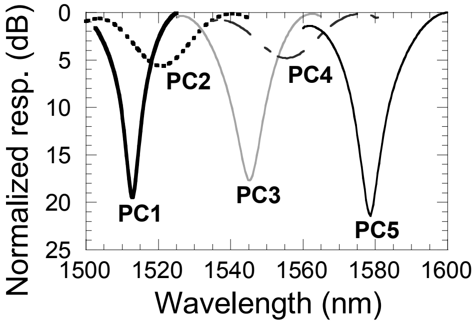


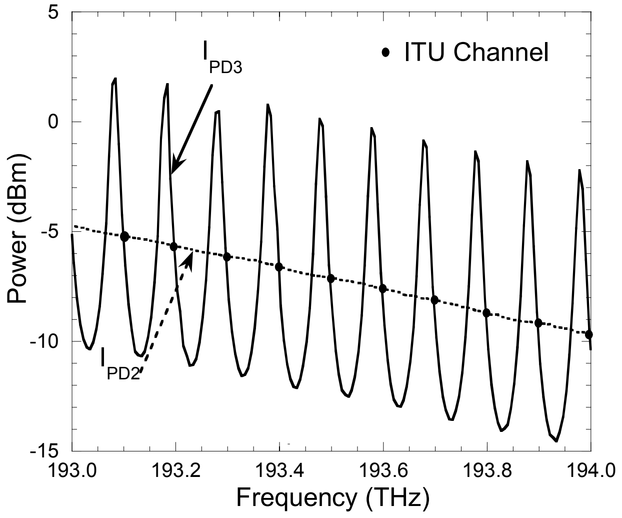
Fig. 6. Spectral responses of the isolator and a polarizer for different input polarization states.

to the crossover point of the two curves. The frequency spacing between the adjacent crossover points is determined by the FSR of the FP etalon, which is designed to match the DWDM channel spacing. The spectral response of the PD3 signal is ideal for monitoring tunable lasers since it has sharp variation around the locking point and can differentiate the responses among the channels. Figure 7(b) shows the stable and monotonic responses of PD2 around 10 channels of 100-GHz spacing. The monotonic response can help locate the wavelength position when the wavelength falls outside of the wavelength-locking range of the etalon (±20 GHz in our experiments). This is essential for a tunable laser to monitor the potential mode hopping or incomplete-tuning problems.

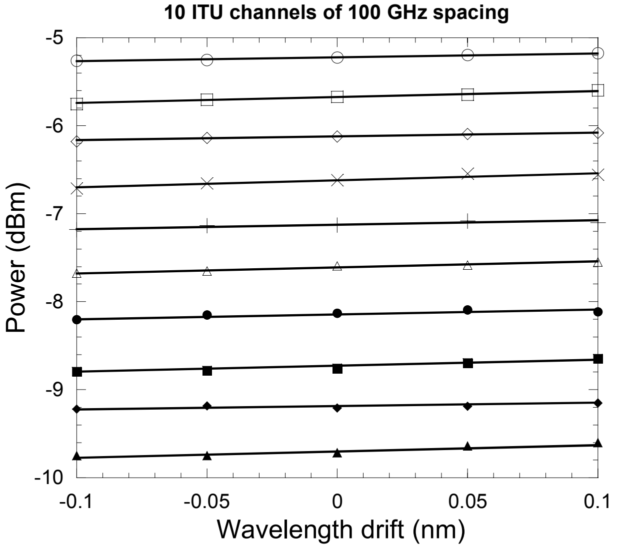
Figure 8 demonstrates the feasibility of simultaneous monitoring of power, wavelength, and channel. In Fig. 8(a) the tunable lasers are tuned to 10 ITU wavelengths. Since the wavelengths are correct, the detected signals of PD2 and PD3 are almost the same. The ratio of the PD3 signal to the PD2 signal is close to 1 for all channels. Under this condition, the ratio of PD2 to PD1 can indicate the channel number. We represent monitoring mode hopping and wavelength drift in Fig. 8(b). The laser is tuned from channel Ch1 to Ch5 and stays at Ch1 and Ch5 for three and four time slots, respectively. The laser encounters mode hopping to Ch2 in the second time slot and wavelength drift in slots 8 and 9. By coincidence, the mode hopping hits an ITU wavelength grid, so the ratio of PD3 to PD2 remains at 1. From the PD2 response one can discover wavelength hopping. On the other hand, for a tiny wavelength drift the PD2 response might not be sensitive enough to reveal the drift from the PD2 signal, but the signal on PD3 can definitely tell the difference.

Regarding the temperature stability of the monitoring module, the wavelength deviation of the FP etalon varies with temperature at a rate of $0.011\ \mathrm{nm}/°\mathrm{C}$[22]. The thermal characteristic of the etalon must be compromised to obtain satisfactory stability and agility. The thermal stability of the polarization-independent isolator is determined by the temperature variation of the Faraday rotation angle for the Bi-YIG film in the rotator. For example, the use of a different film composition or of two-layer Faraday films can achieve $-0.01°/°\mathrm{C}$ of temperature stability in the Faraday rotation angle [23]. Moreover, the wave plate after the isolator can be properly designed to compensate the thermal drift of the isolator response. Similar schemes based on birefringent crystals have been proposed for making wavelength filters [6]. Thus the proposed module can be made to be thermally stable.

We performed a stability test on the CM for eight channels over 12 min and observed tiny deviations, as shown in Fig. 9. When the module is tested over 2 h, the maximum wavelength deviation is less than ±0.13 nm. The deviation is primarily due to the change in the ambient condition since no temperature control was applied to the monitoring module during the measurements. We expect that the wavelength fluctuation will be greatly reduced

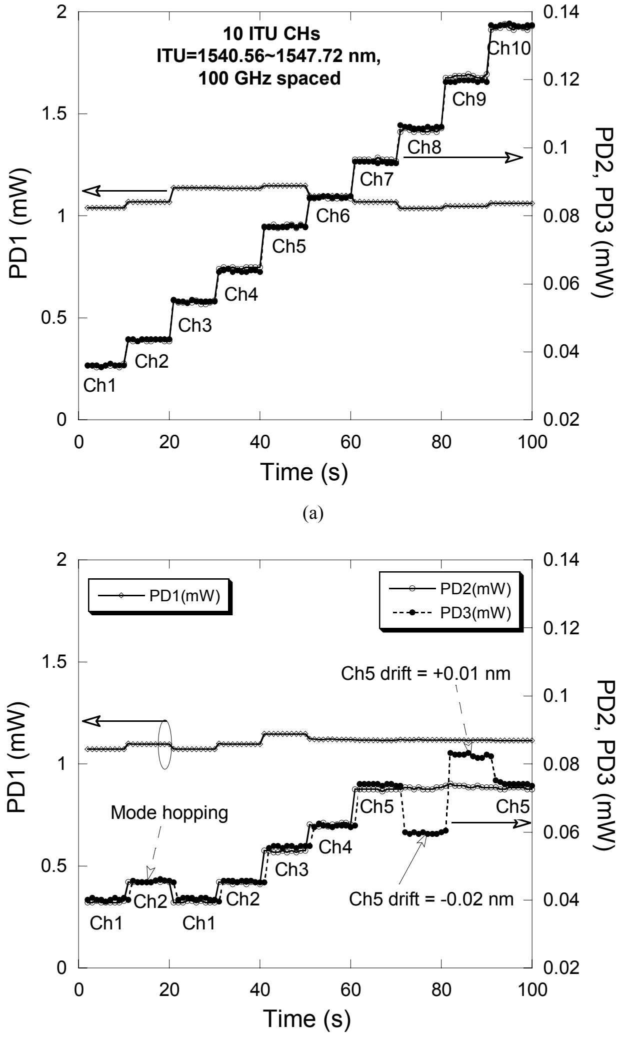


(a)



(b)

Fig. 7. Measured CM characteristics for the compact module shown in Fig. 5(b): (a) spectral responses of PD2 and PD3, and (b) PD2 response versus wavelength drift.



(a)

(b)

Fig. 8. Demonstration of simultaneous power-, wavelength-, and channel-monitoring for continuous tuning to (a) 10 ITU channels and (b) channels with mode hopping and wavelength drift.

when special care is taken to stabilize the temperature. For example, the monitoring module can be packaged with a laser chip and a thermoelectric cooler.

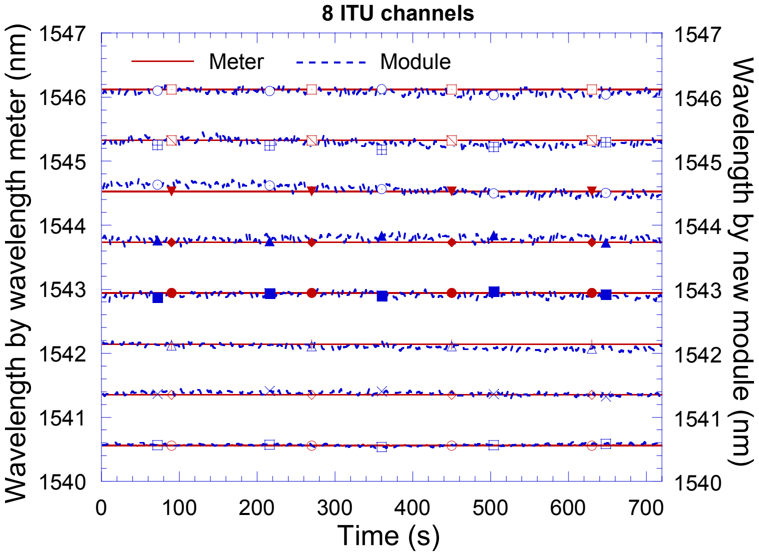


Fig. 9. Passive tunable channel recognition module has an excellent distinction between channels and a stable characteristic for monitoring multiple channels.

The switching time is a key parameter of a TLS, especially for fast switching applications in DWDM networks. It can be defined as the time from the receipt of a channel-switching command to the locking of the TLS at the new channel wavelength. In general, it takes at least several nanoseconds to look up the tuning table and perform wavelength switching for various monolithically integrated tunable lasers. The processing time of the wavelength- and channel-monitoring module must be much shorter than the switching time. Our proposed module can provide a relatively faster response than the existing schemes since it uses passive components and does not require signal dithering. However, the speed of wavelength stabilization still depends on the tuning mechanism of a TLS and the response speed of the signal-processing electronics.

4. Discussion and Summary

The multiparameter monitoring module can be applied in a networking node such as a multiwavelength optical switching node or a reconfigurable optical add–drop node. It can also be used for monitoring a tunable wavelength converter, which typically requires a tunable laser with accurate and stable wavelengths. Because of the polarization wandering after transmission, a polarization recovery module (PRM) is required for these applications to adjust the input signal polarization to the monitoring module. The PRM can be made from a combination of an optical circulator and wave plates [24] or from a combination of a PC with a polarization-monitoring module [25].

The module can also be applied to monitor the channel wavelength and even the OSNR of a CWDM signal. CWDM systems use uncooled laser sources to reduce cost, so the channel wavelengths are allowed to drift with temperature change. For CWDM links with optical amplifiers, monitoring of the channel wavelength and OSNR with optoelectronic modules might be beneficial since it obviates the need for high-speed optoelectronic sampling. In particular, channel wavelength monitoring can help the amplifier nodes or receivers adjust their optical filters to suppress the amplified spontaneous emission (ASE) noise. If semiconductor optical amplifiers are used, it is possible to adjust the bias current according to the channel wavelength monitoring to obtain the optimal noise figure. The required wavelength-monitoring function can also be realized with the isolator-based modules. Besides, the combination of an isolator and a polarizer functions as a tunable notch filter. Thus it can be used to suppress the signal for measuring the noise power and to obtain the OSNR for CWDM channels. The OSNR monitoring for a CWDM signal is not trivial since the channel wavelength is allowed to drift and the signal polarization varies with wavelength. The isolator-based module can have the advantage of a simple tuning mechanism. How to design the monitoring module to meet the low-cost requirement of CWDM systems needs further investigation.

In summary, we have proposed an isolator-based module for recognizing the channels of DWDM tunable lasers. The channel monitoring module can be integrated with the power- and wavelength-monitoring paths in a compact module. The isolator can also prevent reflection from the FP etalon and photodiodes from influencing the tunable laser characteristics. We demonstrated its versatility for monitoring different wavelength bands and its feasibility for detecting mode hopping and wavelength drift.

Acknowledgments

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