High accuracy wavelength locking of a DFB laser using tunable polarization interference filter

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A temperature-tunable polarization interference filter (PIF) made of YVO_4 crystal has been presented and applied for wavelength locking of a distributed feedback (DFB) semiconductor laser in dense wavelength-division-multiplexing (DWDM) optical communication systems. This new design offers a flexible way to monitor and then lock an operating wavelength of DFB laser to any preselected point without dead spots. The results show that the laser wavelength can be locked with accuracy better than ±0.01 nm with much relaxed requirement on temperature stability of the filter.

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In dense wavelength-division-multiplexing (DWDM) optical communication systems, the channel spacing of the signals has been prescribed by ITU-T as 25, 50 and 100 GHz, or 0.2, 0.4 and 0.8 nm based on a wavelength of 1552.52 nm, respectively. In order to avoid crosstalk and keep DWDM network in operation, it is usually required for the frequency drift of each laser to be stabilized within 10% of the channel spacing. That is, the permissible frequency drifts are ±1.25, ±2.5 and ±5.0 GHz for frequency spacings of 25, 50 and 100 GHz, respectively. Distributed feedback (DFB) semiconductor lasers are often used as optical transmitters in DWDM systems due to their low cost and straightforward implementation. However, the wavelength drift by chip temperature in a DFB laser is about 0.1 nm/°C, and the wavelength drift over lifetime due to aging can be as large as several hundreds of picometers. Therefore, it is necessary to monitor and then lock the wavelength of each DFB laser in DWDM networks in order to maintain required spacings between adjacent channels.

Most existing monitoring techniques use interference-type optical filters as wavelength discriminators[1−7]. Among them, Fabry-Perot (FP) etalons are especially popular[5−7]. In this letter, we report on the development of a tunable polarization interference filter (PIF) for wavelength monitoring and locking of a DFB laser. The filter consists of a pair of polarizers and a birefringent plate sandwiched between them. The birefringent plate used is made of yttrium orthovanadate (YVO_4), a positive uniaxial crystal which is transparent in the wavelength range of $0.4 - 5$ μm. Its large birefringence ($n_e - n_o = 0.2039$, at 1.55 μm and 25.0 °C) makes optical devices more compact. Moreover, both the birefringence and dimensions of YVO_4 crystal are sensitive to temperature. This means the transmission spectrum of the filter can be tuned by controlling the birefringence and thickness of the YVO_4 plate via temperature. In our design, this is realized with a heating coil surrounding the plate. By changing the temperature of YVO_4 crystal, the transmission spectrum of PIF can be tuned easily to meet the requirement of wavelength locking.

The YVO_4 PIF offers a flexible way to monitor and lock the DFB laser wavelength. Contrary to commercially available fixed-wavelength filters, the operation point of the PIF is not limited to the ITU frequency grid, but can be dynamically tuned over a wide wavelength range. As a result, the wavelength locking area can be enlarged without blind spots. Further more, because the PIF is much less sensitive to temperature than FP filter made of silicon[8], the requirement on the temperature control circuitry is obviously relaxed.

The temperature-tunable PIF was fabricated by sandwiching a YVO_4 crystal plate between a pair of parallel polarization beam splitters (PBSs). The crystal plate with the thickness of 14.301 mm was cut in such a way that the *c* axis lies in the plane of the plate surfaces. The size of its cross section is 5×5 mm^2. Thus the propagation direction of normally incident light is perpendicular to the *c* axis. The plate is oriented so that the slow and fast axes are at 45° with respect to the transmission axis of the two PBSs. All light-passing surfaces are antireflection-coated. The transmission spectrum of the filter is a sinusoidal function of the optical frequency[9]. The free spectral range (FSR = 97.3 GHz) of the filter at 42.5 °C was determined by fitting a sinusoidal function to the measured transmission data as shown in Fig. 1. Here we assume that the intensity of the normally incident light is isotropic.

The temperature tuning of the filter is realized by feeding current through a heating coil surrounding the YVO_4 plate. Tuning of the filter by temperature is feasible due to temperature dependence of the birefringence and thickness of YVO_4 crystal. The thermal optical coefficients of YVO_4 crystal are $dn_o/dT = -8.5 \times 10^{-6}$ K^{-1} and $dn_e/dT = -3.0 \times 10^{-6}$ K^{-1}. The thermal expansion coefficient is 4.43×10^{-6} K^{-1} in the direction perpendicular to the *c* axis. In order to measure the temperature of the YVO_4 plate, twelve thermally sensitive diodes connected in series were deposited around it as a temperature sensor. The relation between the output voltage of these diodes and their temperature was measured with a thermocouple thermometer in advance. The measured transmission as a function of the temperature of the filter is shown in Fig. 2. It can be deduced

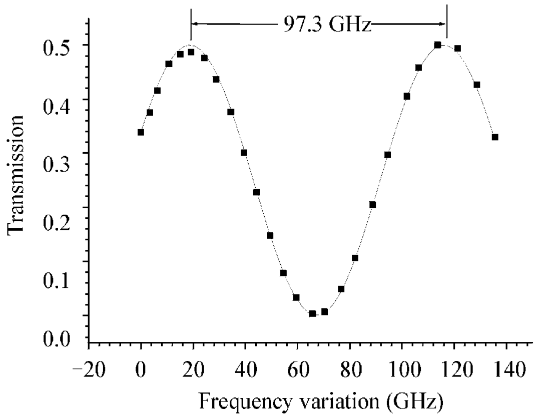

Fig. 1. Transmission spectrum of the YVO4 PIF. Square dots represent measured data at a constant PIF temperature 42.5 °C, and solid line is the fitted sinusoidal function.

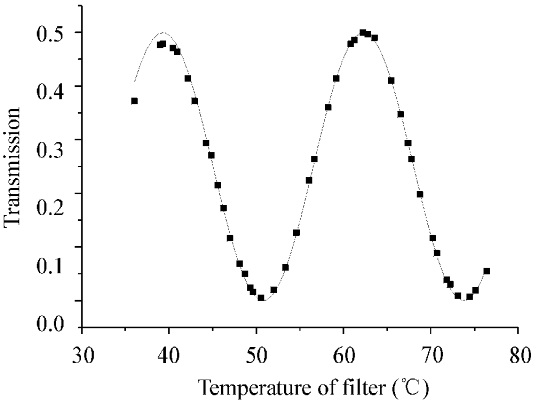

Fig. 2. Temperature dependence of the transmission of the YVO4 PIF. Square dots represent measured data of transmission at $\lambda = 1552$ nm, and solid line is the fitted theoretical function.

that the transmission peak of the YVO4 PIF shifts with temperature by about 4.3 GHz/°C.

Wavelength locking utilizes the wavelength sensitive characteristic of PIF optics transmission to monitor the wavelength and then change the wavelength by adjusting laser chip temperature. For a single channel device operating at certain wavelength, the original value of transmission light intensity of PIF should be stored. During operation, the transmission light intensity is checked periodically and compared with the original value. If it is found to be shifted from the original value, it indicates that the wavelength is shifted and appropriate adjustments need to be done to bring the wavelength back to the original point. For negative slope locking as shown in Fig. 3, if the transmission of the filter is detected to be higher than the original value (see point A in Fig. 3), then the DFB laser chip needs to be cooled so that the laser frequency increases until it reaches the original point C_i; if the transmission is detected to be lower than the original value (see point B in Fig. 3), the chip needs to be heated to decrease the laser frequency.

To be able to lock wavelength with proper accuracy, there have to be certain amplitude and certain slope at the locking point. Therefore, for a fixed filter, there are some dead spots on its transmission curve which we will not able to use for wavelength locking (see areas where transmission is larger than T_1 or smaller than T_2 in Fig. 3). The YVO4 PIF, however, has no dead spots for wavelength locking because its transmission spectrum can be tuned by changing temperature to the position where the locked point is at the midpoint of a curve slope.

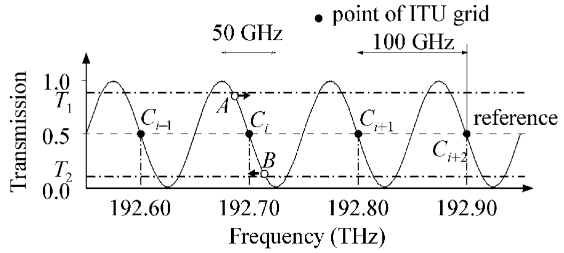

Fig. 3. Wavelength locking process. C_i: the point to which the laser frequency is locked.

From the locking operation principle mentioned above, it is necessary to maintain the transmission spectrum of PIF stable after being tuned to the preselected position for the use of wavelength locking. This was realized by a temperature control circuitry. Because the temperature fluctuation as much as ±0.1 °C can only result in ±0.43 GHz shift in transmission spectrum of PIF, the requirement on the temperature control circuitry can be much loosened. Variations of the ambient temperature did not affect the performance of the device on condition that the PIF operating temperature was kept more than 10 °C above the ambient temperature.

In the wavelength locking device as shown in Fig. 4, about 5% of the total output power of the DFB laser is tapped off for wavelength locking. This portion of light enters the monitor module and splits into two paths. The first path sends light directly to a photodetector (PD_1), which uses the signal as a reference. The second path sends light first through a collimator, then through the PIF and eventually to another photodetector (PD_2). The ratio between the two detector outputs is used to generate a feedback signal to adjust the DFB laser wavelength to the right point. Monitoring the transmitted light intensity ratio of the two paths instead of the

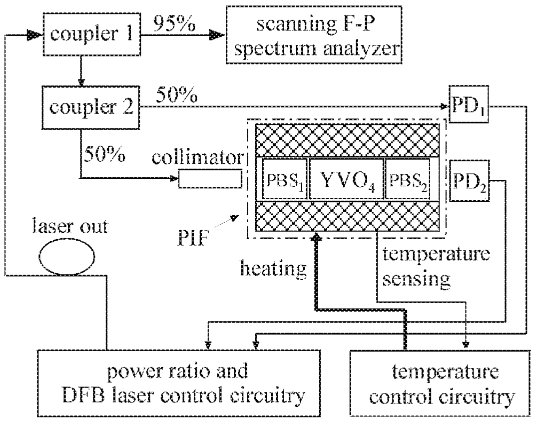

Fig. 4. Experimental setup for wavelength locking of a DFB laser.

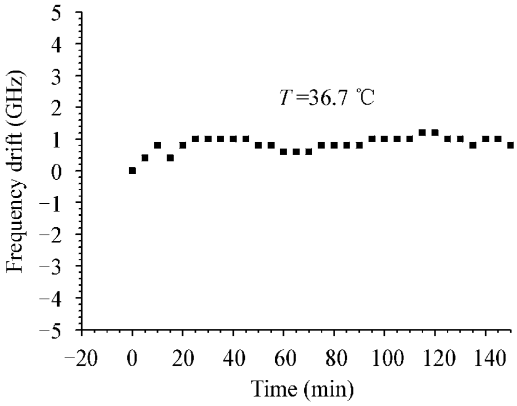

Fig. 5. Measured frequency stability of DFB laser when the PIF temperature was kept at 36.7 ± 0.1 °C.

absolute filter output can exclude not only the variation of the photodiode output due to their case temperature changing and aging, but also the fluctuation of the DFB laser output.

In the experiment, the output power of the DFB laser (JDS Uniphase CQF915/2833 series) was 1.65 mW. The frequency variation was measured by using a scanning FP spectrum analyzer (Coherent Model 240). At the beginning, we changed the filter temperature carefully so that the laser frequency to be locked was at the midpoint of a slope area in the filter transmission spectrum (see Fig. 3). The experimental result is shown in Fig. 5. It can be seen that the frequency stability of DFB laser is less than ±1.25 GHz (i.e., ±0.01 nm) when the PIF temperature was kept at 36.7 ± 0.1 °C during continuous operating time of 2.5 hours.

In summary, we have demonstrated a wavelength locking system that utilizes a tunable PIF made of YVO_4 crystal plate. The transmission spectrum of the filter can be tuned easily and stabilized precisely to any designated point due to its moderate ratio 4.3 GHz/°C of peak frequency shift to temperature change in YVO_4 crystal. Wavelength locking accuracy better than ±0.01 nm for a DFB laser was achieved by use of PIF with temperature stability of ±0.1 °C that has much relaxed requirement on the temperature control circuitry. Therefore, this kind of wavelength locker can be applied in DWDM networks with frequency spacing as small as 25 GHz. Besides this, it can also be used for light source stabilization for optical information, sensing and other measurement applications.

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