Wavelength and power monitoring of DWDM systems using scanning F–P filter calibrated with a F–P laser

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Abstract

A novel technique to overcome the long-term drift and hysteresis of a scanning Fabry–Perot filter was developed and applied to wavelength and power monitoring of DWDM system. By using the comb peaks generated by a temperature-stabilized, near threshold-biased Fabry–Perot diode laser as wavelength reference for the scanning Fabry–Perot filter, wavelength and power measurement accuracy of better than $\pm 10$ pm and 0.2 dB, respectively, were achieved.

Keywords: Wavelength monitoring; Optical power monitoring; WDM applications

1. Introduction

Recent phenomenal growth in DWDM systems as a result of the explosion of Internet traffic called for more wavelength channels as well as narrower channel spacing. Wavelength monitoring and control of DFB lasers [1–8] becomes a critical issue as the channel spacing is reduced. The wavelength of DFB lasers even with temperature stabilization will drift over their 25 years lifetime due to ageing of the devices. DWDM systems with a large number of channels demand more optical output power from lasers [9–11] to compensate for the large insertion loss of the wavelength multiplexers. The laser current of these lasers can be as high as 250 mA and thus the lasers will age much more rapidly. The ageing-induced wavelength drift of these high power lasers could be as large as 0.3 nm [12,13].

Consequently, there is a need for practical high-resolution wavelength monitoring as well as optical power and optical signal-to-noise ratios (OSNR) monitoring. In the last few years there have been considerable efforts to develop wave-
length monitoring techniques for DWDM systems. It has been demonstrated that multiple wavelengths could be monitored by using tunable optical filters [1,2], a sweeping laser with heterodyne detection [3], fiber Bragg gratings [4], an arrayed waveguide grating (AWG) with photodiode array [5,6], and the transparent properties of semiconductor optical amplifier and a Fabry–Perot (F–P) laser [7,8]. Hitherto, perhaps the most practical methods that could monitor multiwavelength, optical power and OSNR of DWDM systems, are those that employed fiber Fabry–Perot tunable filters (FFP-TFs) [1]. FFP-TFs have been commercialized for several years and are commonly used for interrogating FBG sensors [14,15]. However, hysteresis of the piezoelectric transducer (PZT) necessitates constant calibration of the FFP-TFs when used for DWDM monitoring. A reference such as a temperature-stabilized etalon illuminated with an LED light source is normally used as a wavelength reference for calibrating the FFP-TF’s nonlinear wavelength–voltage response. In this paper, we proposed to use a temperature-stabilized low-cost F–P laser for the reference. The laser was operating at low current below the threshold current and thus the ageing-induced wavelength shift is expected to be much less than 0.01 nm over its service life. Our preliminary measurement setup exhibits a wavelength measurement accuracy of better than ±10 pm, monitoring range of greater than 30 nm, dynamic range of 70 dB and is capable of measuring input power as low as ~66 dBm.

2. Experiment and results

Fig. 1 shows the measurement system used to monitor both the wavelength and optical power of a multi-channel system. The system comprised of a F–P laser whose spectrum consists of multiple wavelength peaks and are employed as wavelength reference for the system. The laser was a double channel planar buried heterostructure type diode laser with a threshold current of 11 mA at 25 °C. The center wavelength and mode spacing were 1545 and 1.08 nm respectively. It was temperature stabilized at 22 °C with a stability of ±0.01 °C by using a commercial TEC controller. Typical temperature coefficient of InGaAsP F–P laser is about 0.3 nm/°C and thus we expected the wavelengths of the laser to be stabilized to within ±0.003 nm. The laser drive current was maintained at 10.3 ± 0.01 mA. The FFP-TF had an optical bandwidth and FSR of 0.04 and 48 nm respectively. An optical bandpass filter with bandwidth of 40 nm and center wavelength of 1540 nm was inserted to the system. This filter stopped the optical power outside the monitoring range to reach the photodetectors. An analog-to-digital (A/D) and digital-to-analog (D/A) card installed in a computer was employed to generate a voltage.

Fig. 1. Wavelength and power monitoring of DWDM system using a FFP-TF calibrated with a F–P laser. Electrical and optical connections are shown in dashed lines and solid lines respectively.
signal to the FFP-TF as well as to receive signal from the photodetectors. When a sawtooth voltage was applied to the FFP-TF through the D/A channel, the calibrated spectrum of the F–P laser was scanned by the FFP-TF and detected by photodetector B via the bandpass filter, port 2 and port 3 of the circulator. This output signal was then feed to the A/D channel and was used to calibrate the scanning FFP-TF. Concurrently, the DWDM spectrum to be measured or monitored was scanned by the FFP-TF and the photodetector A via port 1 and port 2 of the circulator and then the bandpass filter. The optical power and wavelength of the DWDM signal can be determined by reference to the calibrated signal measured by photodetector A. Photodetector A which had a sensitivity of $-70$ dBm provided an output voltage that was proportional to the incoming optical power in dBm. The total insertion loss of the circulator, bandpass filter and FFP-TF was measured to be about 4 dB and thus the measurement system was capable of measuring optical power as low as $-66$ dBm.

The wavelength stability of the F–P laser was evaluated experimentally by using an optical spectrum analyzer (Ando AQ6317) to measure its spectrum together with the spectrum of a commercial tunable laser (Santec TSL-210) for more than 8 h. The inset of Fig. 2 shows the F–P laser’s spectrum, biased at 10.3 mA, measured with the OSA with resolution set to 0.02 nm. Fig. 2 shows the measured result of eight of the laser lines (between 1544 and 1553 nm). The initial decrease in the wavelength of both the F–P laser and the tunable laser was due to the warm-up time (>100 min) of the OSA. This result showed that the F–P laser when temperature-stabilized exhibited virtually the same wavelength stability as the expensive commercial tunable laser which had a typical wavelength stability of 5 pm. It is apparent from these results that the F–P laser can be stabilized to better than ±5 pm. The result was limited by the 2 pm readout resolution of the OSA. Better wavelength stability could be expected if a commercial TEC controller with temperature stability of ±0.003 °C [16] was used.

The spectrum of the F–P laser with different bias current at a constant operating temperature of 22 °C was also measured. Fig. 3 shows the measured wavelength shift of one of the F–P laser mode by varying the bias current, the wavelength shift showed a negative slope of $-87$ pm/mA when the laser was biased less than 10 mA. This was because the carrier population increased linearly with the applied current and resulted in blue shift of the wavelength. Close to threshold region, the carrier density generated by the applied current began to clamp and the wavelength shift was gradually reduced which contributed to the flat wavelength to current response region as shown in Fig. 2.

![Graph showing wavelength variation of the temperature-stabilized F–P laser and tunable laser (Santec TSL-210) over 5 h of operation. (Inset: Measured spectrum of the F–P laser when biased at 10.3 mA.)](image)
Fig. 3. When the laser current was increased beyond the threshold current, the wavelength shift reduced significantly and exhibited a smaller positive slope of 1 pm/mA due to the thermal effect and the nonlinear gain suppression [17]. All other F–P laser modes showed similar characteristic in the experiment. Based on these results, we biased the F–P laser at 10.3 mA because the output spectrum was broader and allowed a wider wavelength range of the FFP-TF to be calibrated. This also minimized the wavelength drift due to current fluctuation of the drive electronics.

A computer program was designed to generate a sawtooth voltage signal to drive the FFP-TF via a D/A channel, and the received signal from the photodectors via two A/D channels simultaneously. The F–P laser spectrum was scanned by the FFP-TF and measured by the photodetector B. The peak voltages which correspond to the calibrated wavelength peaks of the F–P laser were stored in the computer. Using these data and a curve-fitting method, a best-fitted curve describing the wavelength–voltage response of the FFP-TF was obtained. The DWDM spectrum to be monitored was fed to the monitoring system via a 5% tapper, scanned by the FFP-TF and then measured by photodetector A. The wavelength and power of the DWDM system were then determined by the best-fitted curve and the magnitude of the signal respectively. The drift of the filter was overcome by repeating the calibration.

The signal sent to the FFP-TF, S(t), is shown in the inset of Fig. 1. The voltage (maximum range –4.8 to 4.8 V) and frequency of the FFP-TF were chosen so that it scanned over 30 nm (i.e., 27 calibrated comb peaks) in 0.5 s. The signal generated by the D/A channel to the FFP-TF was 12-bit long, therefore the scanning resolution of the filter was limited to 7.3 pm (30 nm/2^{12}). This resolution could be improved either by scanning over a smaller wavelength range or by using a D/A card with larger number of bits. The output voltage of the photodetectors was in the range of 1–4.5 V which corresponds to the input optical power of –70 to 0 dBm. The A/D channel used was 16-bit long and if noise is ignored, the resolution of the optical power measurement would be 0.001 dB (70 dB/2^{16}). The bit length was adequate since the system’s resolution will be limited by noise. Fig. 4 shows the result of a single scan, the voltage range (–4.8 to +4.8 V) was divided equally into 4096 samples (2^{12} samples) and applied to the FFP-TF. The sample positions corresponding to the 27 peak voltages measured by the photodetector B were stored and assigned to the 27 calibrated wavelengths. This figure clearly shows the nonlinear wavelength–voltage response of the FFP-TF. Wavelength error of larger than 0.6 nm would result if the wavelength was simply mapped by the

Fig. 3. Wavelength shift of one of the F–P laser mode as a function of bias current at a constant operating temperature of 22 °C.

Fig. 4. The nonlinear wavelength–voltage response of the FFP-TF measured by applying a sawtooth voltage to the FFP-TF and fitting the output voltage peaks to the calibrated F–P laser comb peaks (●).
best-fitted straight line as shown in Fig. 5. Fig. 6 shows the improvement in wavelength measurement error by curve-fitting the result with a sixth-order polynomial and the resulting error is less than 10 pm.

The monitoring system was tested by measuring the wavelength of eight singlemode lasers spaced at 100 GHz apart for about 30 min. Fig. 7 shows the wavelength error versus the wavelength measured by the OSA for the eight channels. The wavelength stability of these lasers were specified at 10 pm (<1 h). These results demonstrate that the monitoring system was capable of measuring wavelength with an accuracy of ~ ±0.01 nm. The results were in fact limited by the wavelength stability and resolution of the lasers and the OSA used in the experiment. By using a 16-bit D/A card to increase the scanning resolution from 7.3 to 0.45 pm, and a TEC controller with temperature stability of ±0.003 °C [16] to improve the wavelength stability of the F–P laser, wavelength accuracy of the monitoring system better than 2 pm was believed to be achievable. The power measurement accuracy of the system was also evaluated using a constant power laser source, and 0.2 dB accuracy was achieved for input power as low as −66 dBm.

Another important issue in using F–P laser as the reference is the long-term stability of its peak wavelengths. Fukuda [18] has shown that there is a strong correlation between degradation and wavelength shift in semiconductor lasers. Degradation depends on the laser current density, $J$, through the relation $J^n$, where $1.5 \leq n \leq 2.0$ [19]. Since the F–P laser is driven at a value less than one-tenth of the biased current of DFB lasers [9], its degradation is expected to be two orders of magnitude smaller and thus its wavelength shift throughout its service life is expected to be much smaller than 0.01 nm when compared with laser biased well above threshold [13]. Intensity fluctuation of the F–P laser due to mode-partition is not an issue here since only peak wavelengths are used to calibrate the FFP-TF.

3. Conclusion

In conclusion, we have demonstrated a channel monitoring system that utilizes FFP-TF and a
referencing source based on a low-cost F–P laser. By biasing the F–P laser around the threshold region, we have also shown that the wavelength drift due to current fluctuation can be minimized. More importantly, this also delayed the ageing of the laser significantly as a result of the much smaller drive current. A computer program which incorporated signal generation, receiving information, signal processing and provided measurement readout was implemented in our experimental setup. Wavelength and power monitoring of eight channels spaced 0.8 nm apart was conducted and an accuracy of ±0.01 nm and 0.2 dB respectively was achieved.

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References

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