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Device for simultaneous monitoring of the channel wavelengths and power levels in a DWDM system

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A compact and cost-effective device for monitoring wavelengths and power levels of WDM channels labeled with pilot tones is presented. The device utilizes a tunable silicon etalon and a simple sampling scheme to identify and analyze the channels directly from the optical multiplex. The operation is demonstrated in a four-channel system. Extension to a large number of WDM channels is evaluated through simulations. © 2004 Optical Society of America

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1. Introduction

The increase of channel density and total channel number in future dense wavelength-division-multiplexed (DWDM) systems sets stringent requirements for the wavelength stability of the transmitters. Continuous monitoring of the allocated channels, channel wavelengths, and channel power levels becomes essential for dynamically controlling and supervising the DWDM channels. Spectrum analyzers are commonly used for this purpose, although they are cumbersome and expensive.

Tunable Fabry–Perot etalons have been proposed for measuring the wavelengths and power levels of a low number of channels in transmission geometry [1]. Pilot tones have been used in combination with a fixed Fabry–Perot etalon or arrayed-waveguide gratings to monitor a higher number of channels [2–4]. However, these methods require either complex signal processing or too many expensive optical components.

In this paper we report on a simple and cost-effective method for accurate monitoring of channel wavelengths and power levels by use of a single tunable etalon [5, 6], a photodetector, and a microcontroller [7]. The method is based on the detection of a pilot tone by sweeping an etalon fringe across a channel while determining the pilot tone amplitude with a simple sampling scheme [8]. We apply the method to a four-channel WDM system and study the feasibility of extending the technique to a higher number of channels through simulations.

2. Operation of the Monitoring Device

The proposed device concept is based on a wavelength-scanning etalon and a sampling scheme. This combination allows each channel in a WDM network to be directly measured from the optical multiplex without interference from the other channels. By measuring a channel at a time, it is possible to scan through the wavelengths and power levels of all the channels in a WDM system. This approach relies on pilot tones, and therefore each channel should be modulated by a weak sinusoidal subcarrier with a unique kilohertz (kHz) range frequency [9]. The labeling of the channels is necessary to distinguish one specific channel from the WDM multiplex, since multiple transmission fringes of the etalon are likely to coincide with the WDM channels at any time.

To measure one channel directly from the WDM signal, we branch a small portion of the power to the channel-measuring device. A fringe of the tunable etalon is swept across the wavelength range specified for the particular channel. The sweep is executed in small wavelength steps of 0.5 to 10 pm. The amplitude of the tone is measured at each step by a sampling system that filters the other tones. As the bandwidth of the fringe at over 100 pm (FWHM) is much broader than the linewidth of an average telecommunication laser, the completed sweep reproduces the shape of the etalon fringe with a center wavelength that is the same as the laser's and a peak value that is directly proportional to the channel power. The described operating principle of the monitoring system is outlined in Fig. 1.

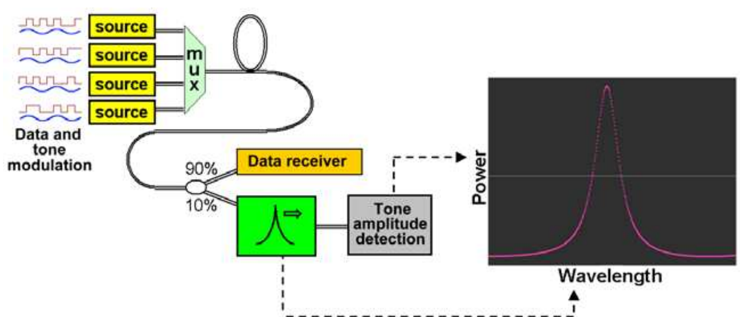

Fig. 1. Operating principle of the monitoring device.

To extract the information of the channel wavelength and power from the measured data, we use the simple approach illustrated in Fig. 2. First, a threshold level is established at 1 to 5 dB below the maximum value of the measured tone amplitude. Subsequently, a quadratic equation is fitted to the measurement points lying above the threshold level. Finally, the position of the peak of the fitted curve gives the channel wavelength and power.

2.A. Tunable Etalon as a Scanning Reference Filter

The optical filter employed in the monitoring system is a solid Fabry–Perot etalon fabricated from a double-side-polished silicon wafer [5]. The thickness of the etalon is 380 µm, which is standard for silicon wafers. Three pairs of silicon dioxide and silicon nitride layers were deposited on both surfaces of the etalon to form dielectric quarter-wave mirrors. The reflectivity of the mirrors was determined to be 66% at the nominal wavelength of 1.55 µm, resulting in a fringe bandwidth of 14 GHz (FWHM). The free spectral range (FSR) of the etalon is determined by the refractive index of silicon ($n_{\mathrm{Si}} \sim 3.4$), and the etalon thickness and is therefore 110 GHz. The area of the etalon chip is 10 mm $\times$ 6 mm.

The transmission of the etalon is tuned by changing the etalon temperature. For this purpose the etalon has two molybdenum thin-film resistors deposited on one of its sur-

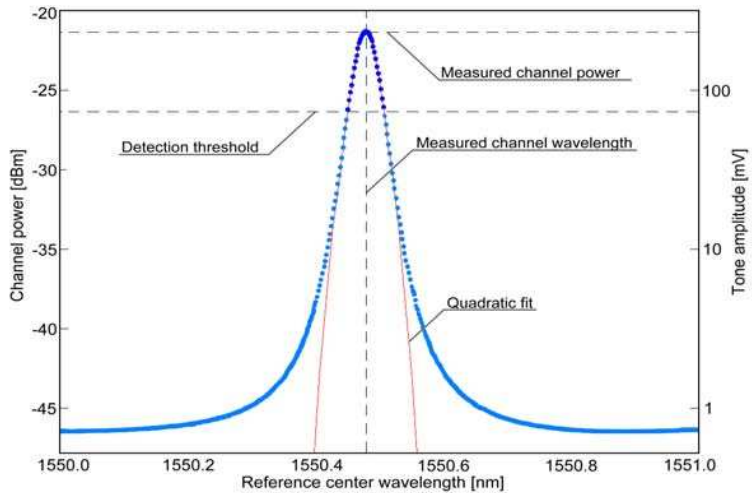

Fig. 2. Extracting the wavelength and power level from the measured data.

faces. The inner resistor is for heating the etalon, and the outer one is for measuring its temperature (see Fig. 3). The resistances of the resistors are 35Ω and 1.6kΩ at room temperature, respectively. The resistors are placed concentrically in a circular pattern to provide a temperature distribution that is as uniform as possible in the area where the laser beam enters the etalon. Utilizing analog-integrator-type feedback from the measuring resistor to the heating resistor, we can rapidly and accurately tune the temperature and stabilize it at a desired value above room temperature. The etalon chip, its resistances, and the tunable transmission spectrum are presented in Fig. 3.

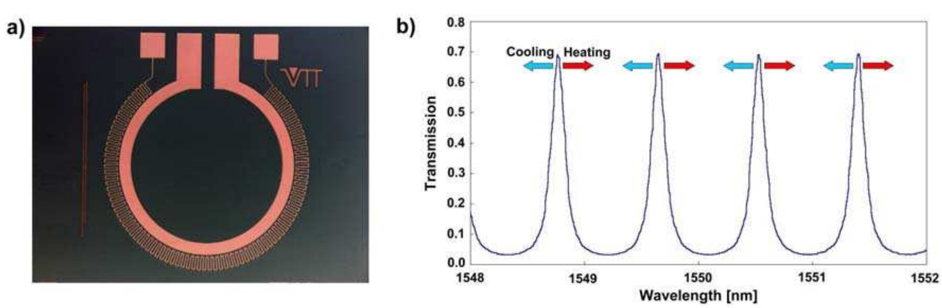

Fig. 3. (a) Microscope image of the silicon etalon showing the two temperature controlling resistors on the etalon surface. (b) Part of the transmission spectrum of the etalon at 1.55 μm, showing four fringes and their temperature tuning.

The fringe visibility reaches its maximum value of 20 dB at the wavelength of 1.45 μm. The visibility drops to 10 dB on either side of the peak value at 1.2 μm and at 1.7 μm. At these wavelengths the bandwidth of the fringes has increased to 35 GHz. These values effectively set the limits for the operating range of the entire monitoring device.

The resonance wavelengths of the etalon depend on its optical thickness as $\lambda_m = 2n_{\mathrm{Si}}d/m$, where $n_{\mathrm{Si}} = n_{\mathrm{Si}}(\lambda, T)$ is the refractive index of silicon, $d = d(T)$ is the physical thickness of the etalon, and m is the mode number of the fringe. For the temperature and wavelength dependence of n_{Si}, we have employed the model of Ref. [10], with a value of 1.5×10^{-4} 1/K for the temperature coefficient of silicon. Using these values, we find that the etalon fringe moves 71 pm for a 1 K change in the temperature. This means that a temperature change of 13.6 K is needed to shift the transmission spectrum for one full FSR in the 1.55-μm region. Hence at maximum, a change of ±6.8 K is required for tuning a fringe to any selected wavelength value in the operation range of the device.

The device constructed in this work consists of a temperature-controlling circuit, monitoring circuitry, a digital control interface, control software, and the etalon itself placed in an air gap formed between two fiber-optic collimators. The temperature is controlled with a 16-bit digital-to-analog converter providing stabilization of the temperature to 2^{16} discrete values in intervals of 3.2 mK. The successive values correspond to a shift of 0.2 pm in the transmission spectrum of the etalon. A software routine has been developed to calculate the needed temperature tuning from a reference temperature to drive a fringe to any desired wavelength in the operating range with an absolute accuracy of better than 1 pm [6].

The tuning repeatability of the etalon based reference has been investigated by continuously measuring a laser wavelength by scanning a the line with the etalon for 100 h with a 3-s repetition rate. All the measured values for the laser wavelength were found to be within ±300 fm.

2.B. Detection of the Labeled Channels

Weak sinusoidal pilot tones have been employed to label WDM channels to identify their presence in an optical network. We apply these tones to evaluate the power levels of the WDM channels. The amplitudes of the tones were set to 10% of the average optical power in a channel. A constant and accurately set ratio between the tone amplitude and the channel power provides the means to determine the power of any channel by simply measuring the amplitude of the tone. Since the optical signal in such a WDM network would be a multiplex of the various data and pilot signals, a method for distinguishing the various tones from each other is needed. The method is mathematically simple.

A part of the WDM signal is tapped from the network to a detector. From this signal, the data carrying gigahertz-range frequencies are filtered out and only the multiplex of the kHz-range pilot tones is preserved. Subsequently, this signal is converted from analog to digital, utilizing a sampling frequency, f_s, exactly four times greater than the tone to be measured. The principle of this sampling scheme is illustrated in Fig. 4.

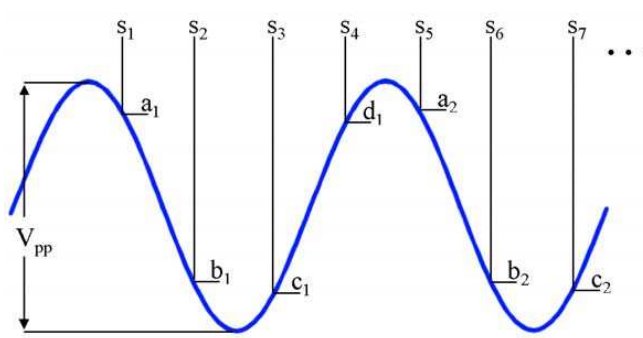

Fig. 4. Principle of the sampling system implemented in the monitoring device.

The sampling is conducted in such a way that every fourth sample is always summed together, i.e., the 1st, 5th, 9th, ... samples $(a_1, a_2, a_3, \ldots)$ are added to Σa, the 2nd, 6th, 10th, ... $(b_1, b_2, b_3, \ldots)$ to Σb, and so on. This results in four sums Σa, Σb, Σc, and Σd of which the peak-to-peak tone amplitude can be calculated as

$$V_{pp} = \frac{4}{n}\sqrt{(\Sigma a - \Sigma c)^2 + (\Sigma b - \Sigma d)^2}, \tag{1}$$

where n is the total number of samples. Utilizing this kind of sampling scheme has many benefits. It detects only the frequency of interest, $f_s/4$, and averages out all other frequencies, if the number of samples, n, is large enough. Also, calculating the four sums and the tone amplitude from them is mathematically fast compared with, e.g., making fast Fourier transforms. This makes it possible to perform the computing with virtually any microcontroller and thus keeps the total component cost to a minimum.

Determining the optimum number of periods to be sampled is important for the accurate operation of the detection system. A value that is too low will lead to poor filtering of the other tones. The maximum applicable sampling time is limited by the drift between the clock that generates the tone in the transmitter and the clock that controls the sampling at the monitoring device. If the time shift of these clocks, $\Delta t = \phi/(2\pi f)$, starts to increase to the same magnitude as the total sampling period, significant attenuation in the value of the detected tone will occur.

Gain cross saturation caused by slow erbium-doped fiber amplifier (EDFA) gain dynamics should not cause a problem at modulation frequencies higher than 10 kHz and at moderate pump and signal powers. In the case of a highly saturated EDFA, the modulation frequency can be raised to over 100 kHz to make sure no interchannel modulation occurs. Above this limit the device is transparent to different data rates and modulation formats [11]. Modulation frequencies higher than 100 kHz are feasible with the proposed device concept.

3. Evaluation of the Performance

The performance of the device when monitoring a high number of channels was evaluated through simulations. A multiplex of several pilot tones was generated and the amplitude of a tone was calculated by use of the presented sampling scheme. A frequency offset of 5 Hz was included to model the effects of expected frequency drifts of standard crystal oscillators. The pilot tone frequencies were in the 50-kHz region with a spacing of 500 Hz between them. The results of the simulation are presented in Fig. 5.

For a low number of channels, sampling for 500 tone periods is sufficient to filter out the other pilot tones and obtain an accurate value for the tone amplitude. As the number of channels is increased to 25 or 50, a longer sampling period of 1000 to 2000 is needed to retain an adequate accuracy. A higher number of sampled periods will lead to poor accuracy because the clock does not remain quasi-synchronized. Increasing the number of sampled periods will also eventually lead to a longer measuring time as the sampling becomes the limiting factor in the measurement speed as opposed to the temperature tuning of the etalon, which otherwise is the bottleneck.

When the Fabry–Perot etalon is placed in front of the detector, the neighboring tones that do not coincide with any of the transmission fringes of the etalon are attenuated. With a WDM channel spacing of 100 GHz and a FSR of 110 GHz of the etalon, only every eighth or ninth tone is not significantly attenuated. The etalon effectively cuts nearly 80% of the unwanted tone signals improving the device accuracy. The attenuating effect of the etalon to the neighboring pilot tones is presented in Fig. 6. In the simulation the channel under measurement is at 1550 nm and therefore has a unity transmission.

4. Measurement Results

The accuracy required in the quasi-synchronization of the pilot frequency and the sampling frequency was investigated by conducting the following measurement. One WDM channel

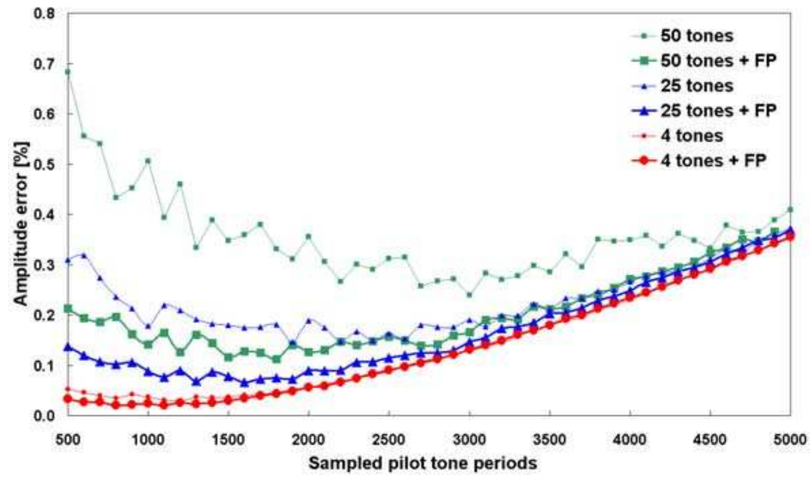

Fig. 5. Simulation of the accuracy of amplitude measurement with a large amount of channels.

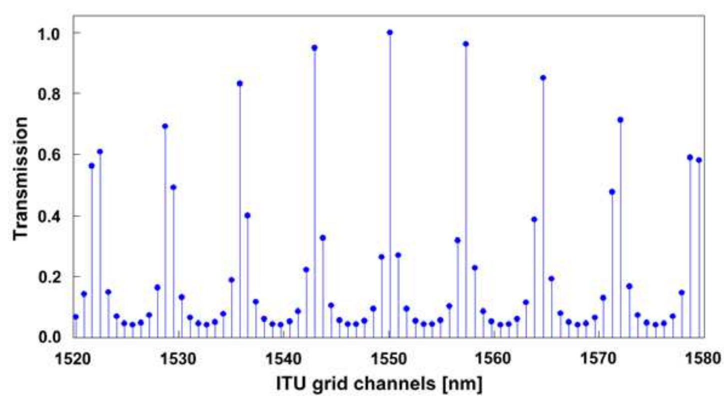

Fig. 6. The attenuating effect of the etalon with a FSR of 110 GHz to the 100-GHz-spaced WDM channels and their respective tones.

was labeled with a 50-kHz pilot tone and the tone was sampled with the required 200-kHz rate, using the monitoring device. Subsequently, the pilot tone frequency was detuned from its nominal frequency and the resulting attenuation was recorded. The measurement was repeated for three different sampling lengths, and the results are presented in Fig. 7.

The pilot tone spacing needed to suppress the cross talk of the neighboring channels below an acceptable level can be evaluated from the presented results. A minimum is found to occur each time the pilot tone frequency offset corresponds to a phase shift of $n2\pi$. The minima can be used to an advantage by selecting the channel spacing to coincide with these dips to further improve the filtering of the pilot tones.

The device concept was tested in a four-channel WDM testbed. A single WDM channel was monitored while three distributed feedback lasers directly modulated with a 2.48-Gbit/s pseudorandom bit sequence were used as the interfering channels. The power levels of the interfering channels were attenuated to -32 dBm. A sampling time of 500 periods was chosen, and a pilot tone modulation depth of 10% was utilized in order not to degrade the bit-error rate of the data stream. The used ITU-T channel numbers [12], channel wavelengths, and pilot tone frequencies are listed in Table 1.

The measurement results for the power and wavelength of channel 33 are presented in Fig. 8. At time t_0, the tone of the detected channel is activated. Between t_1 and t_2, the power of the detected channel is first lowered to -40 dBm and then raised to the -32-dBm power level of the other channels. At t_3 through t_5, first other tones are turned off, the data modulations of the other tones are turned off, and finally the optical carriers of the other three WDM channels are turned off. At t_6, the pilot tone of the detected channel is deactivated.

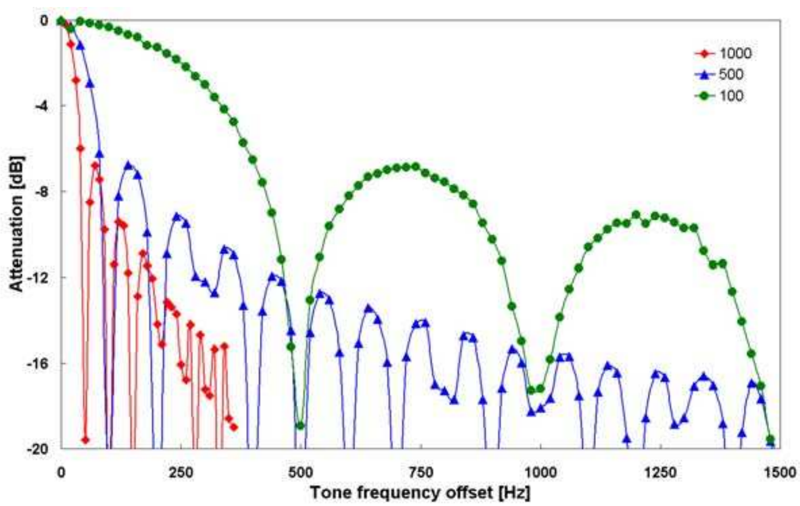

Fig. 7. Frequency sensitivity of the digital filter.

The detected wavelength of channel 33 remained within ± 5 pm of the nominal value of 1550.918 nm through the entire measurement. The deviation of the power measurement was better than 0.1 dB. The power and wavelength measurement accuracy of the device was also tested at higher power levels in the -10-dBm region, and a significant improvement was achieved. At high power levels the accuracy is limited only by the 1-pm accuracy in the determination of the etalon resonance wavelength.

The shortest duration of a single measurement that retained the device accuracy was ~ 1 s. This is limited mainly by the tuning speed of the etalon, which is ~ 2 nm/s, and by the fact

Table 1. **Channel Numbers, Wavelengths, and Pilot Tone Frequencies Used in the Measurement**

ITU-T Channel	Wavelength (nm)	Pilot Tone Frequency (kHz)
31	1552.524	51.28
33	1550.918*	48.78
35	1549.315	50.00
37	1547.715	51.28

*Detected channel.

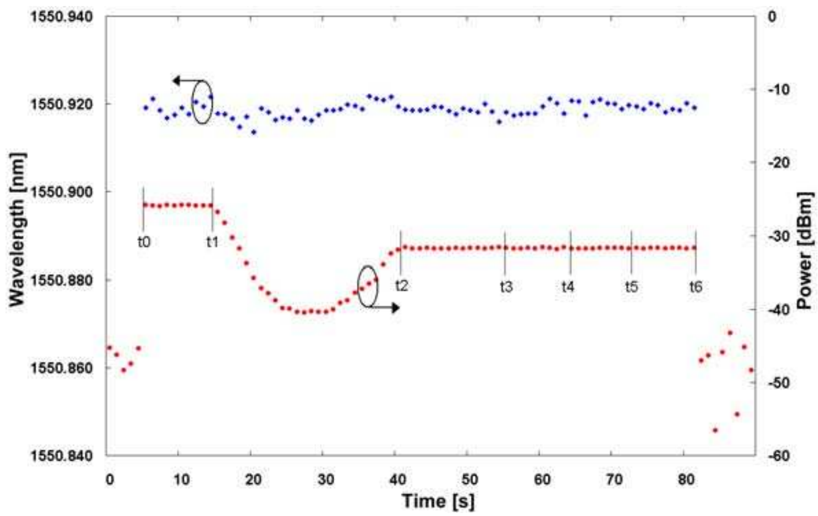

Fig. 8. Power and wavelength measurement results as a function of time.

that the temperature must be retuned to a new value before the next measurement can start. Averaging 500 periods for each point and sampling at 50 points for each sweep, the time consumed for the sampling is 250 ms/channel. Increasing the number of points measured or the sampling length significantly from these values will make the sampling the limiting factor on the speed of the device. The speed could potentially be increased by a few means. Reducing the etalon size would make it respond faster to temperature tuning. Also, limiting the width of the wavelength range to be scanned per channel to the proximity of the last measurement result would also decrease the time consumed by one measurement.

5. Conclusion

In this paper we have presented and demonstrated a practical device concept for cost-effective DWDM power and wavelength monitoring. The concept makes use of a simple digital filter to detect the pilot tone of a channel from which the channel power level can be measured. The WDM channel wavelength is measured with an accurate scanning Fabry–Perot etalon with an accuracy of better than ± 5 pm, depending on the power level of the channel. The proposed device provides a reliable and accurate means to monitor a large number of channels in a DWDM network with a minimum number of optical components.

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