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# Wavelength reference for optical telecommunications based on a temperature-tunable silicon etalon

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A wavelength reference based on a temperature-tunable silicon Fabry–Perot etalon is presented. The device provides a compact and cost-effective solution for calibration of the wavelength scale from 1.3 $\mu$m to 1.7 $\mu$m. The reference is fully automated, needs a single characterization, and operates without an absolute wavelength reference. The performance of the device was estimated by comparing its fringes against acetylene absorption lines. The wavelength differences measured were found to be less than 1 pm.  [DOI: 10.1063/1.1590746]

## I. INTRODUCTION

Over the last few years, the wavelength range applied in wavelength-division multiplexed (WDM) transmission systems has been expanded and the channel spacing has been reduced. This has set new requirements for the standards employed to stabilize and monitor the channel wavelengths. Molecular absorption lines do provide highly accurate absolute references.[1–3] With linear absorption techniques, relative wavelength accuracies of $10^{-8}$ have been achieved. However, these absorption lines offer only a limited number of reference wavelengths that do not necessarily coincide with the International Telecommunications Union (ITU) channel grid.[4] Moreover, suitable gases are not readily available for all utilized wavelength bands.[5]

To overcome the shortcomings of the absolute wavelength references, various stable and tunable filters have been employed as relative references. Fiber Bragg gratings offer a simple and cost-effective way to fabricate a reference for practically any needed wavelength.[6] A wavelength accuracy of $10^{-6}$ is typically achievable. However, the convenient operating range of a single reference is often restricted to about 3 nm because of the limitations of the temperature tuning often used to tune and stabilize fiber Bragg gratings.

Etalons are widely used as wavelength references as they are uniformly applicable to a broad spectral range.[7] The transmission spectrum of an etalon consists of periodical fringes. These can be utilized either individually by tuning one of the fringes to a required wavelength or by using a broader span of the spectrum as a comb offering multiple references.[8] A typical accuracy achieved with an etalon-based reference has been from $10^{-5}$ to $10^{-6}$. Etalons and their tuning mechanisms are, however, susceptible to drifts due to aging.

We have built a versatile and cost-effective wavelength reference using a novel concept based on a temperature-tunable Fabry–Perot etalon made of silicon. The temperature dependence of the refractive index of silicon has been utilized to realize the wavelength tuning and stabilization of the etalon.[9] The developed device can be set to reference any wavelength from 1.3 $\mu$m to 1.7 $\mu$m in 1 s with an accuracy adequate for the needs of the WDM systems of the future.

## II. TUNABLE SILICON ETALON

The frequency discriminator utilized in the developed wavelength reference is a solid silicon Fabry–Perot etalon fabricated from a double-side polished silicon wafer.[5] The thickness of the etalon is 380 $\mu$m, which is a standard silicon wafer thickness. To increase the finesse of the cavity, three pairs of dielectric quarter-wave mirrors have been deposited on both sides of the etalon. Silicon dioxide and silicon nitride were used as the materials for the multilayer coatings since they have high transmission at the wavelengths of interest and have appropriate indices of refraction. The free spectral range (FSR) of the etalon is determined by the refractive index of silicon and the etalon thickness. It was measured to be about 110 GHz. The reflectivity ($R$) of the mirrors was determined by fitting an Airy function to the measured transmission spectrum. At a nominal wavelength of 1.55 $\mu$m, the bandwidth of a fringe is 14 GHz (full width at half maximum) indicating that the reflectivity is 0.66. The dimensions of the etalon chip are $10\times6$ mm$^2$.

To provide temperature stabilization and tunability, the etalon has two molybdenum thin-film resistors deposited on one of its surfaces as presented in Fig. 1. One of the resistors is for heating the etalon and the other one is for measuring the etalon temperature. The nominal resistances of the resistors are 35 $\Omega$ and 1.6 k$\Omega$. The resistors are placed concentrically in a circular pattern to provide a temperature distribution which is as uniform as possible at the area where the beam enters the etalon. The stabilization is realized by utilizing an analog integrator-type feedback. As warming of the etalon is realized actively with the heating resistor and cooling by convection only, heating is much faster than cooling in low operating temperatures as illustrated in Fig. 2. The two horizontal dashed lines represent the maximum tuning range of $\pm7$ K that is utilized in the operation of the device. Even though the temperature tuning would operate much faster at higher operating temperatures, temperatures in the

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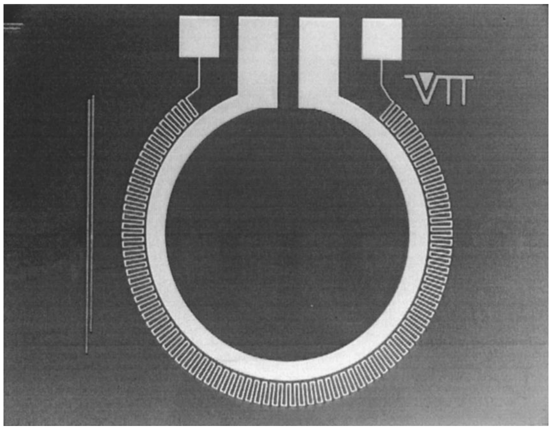


FIG. 1. Integrated heating and temperature sensing resistors deposited on the surface of the etalon.

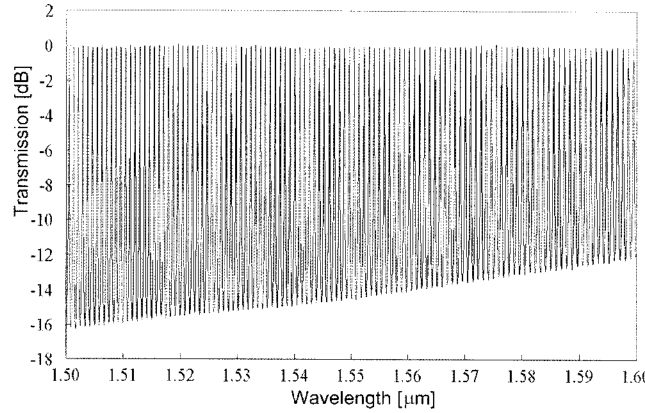


FIG. 3. Measured transmission of the etalon from 1.5 $\mu$m to 1.6 $\mu$m.

range of 50–60 °C were favored since at these temperatures the polarization dependent wavelength shift was at its smallest at around 0.5 pm.

To determine the transmission properties of the etalon on a broad wavelength range, the transmission spectrum was measured from 1.5 $\mu$m to 1.6 $\mu$m. The result of the measurement is presented in Fig. 3. The maximum transmission is normalized to zero and therefore the 1.4 dB attenuation of the etalon and the collimating system is not observable. It can be noticed that the visibility of the fringes increases toward shorter wavelengths. This indicates that the maximum reflectivity of the etalon mirrors lies below 1.5 $\mu$m. Transmission measurements were also conducted at the 1.3 $\mu$m region. Based on the measurement results, the broadband transmission spectrum was simulated and a part of it is presented in Fig. 4. From the simulation results, the operating range of the wavelength reference was evaluated to be from 1.2 $\mu$m to 1.7 $\mu$m. Outside this wavelength range, the reflectivity of the mirrors is decreased to such an extent that accurate and proper operation of the device is no longer guaranteed due to increased bandwidth and reduced visibility of the fringes. The maximum visibility of the fringes is ~20 dB at 1.45 $\mu$m. At 1.2 $\mu$m and 1.7 $\mu$m, the performance of the device is still adequate, however, the visibility is reduced to 10 dB and the bandwidth of the fringes to ~35 GHz.

The refractive index of silicon exhibits a dependence on both the temperature and the wavelength. Therefore, an accurate model for it should be employed. The refractive index can be modeled by[10,11]

$$n_{\mathrm{Si}} = 3.416\,96 + \frac{0.138\,497}{(\lambda^2 - 0.028)} + \frac{0.013\,924}{(\lambda^2 - 0.028)^2} - 2.09 \times 10^{-5}\lambda^2 + 1.48 \times 10^{-7}\lambda^4 + dn \cdot (T - T_0), \qquad (1)$$

where $dn$ represents the temperature coefficient of silicon with a value of $1.5 \times 10^{-4}$ 1/K, $T_0$ is the ambient temperature of 293 K, $T$ represents the temperature of the silicon chip in Kelvin, and $\lambda$ denotes the wavelength in micrometers. Once the refractive index of silicon is known, the center wavelengths of the fringes can be calculated from

$$\lambda_m = \frac{2 n_{\mathrm{Si}}(\lambda, T) d(T)}{m}, \qquad (2)$$

where $m$ is the mode number of the fringe and $d(T)$ is the thickness of the etalon with temperature dependence.

## III. WAVELENGTH REFERENCE

The developed wavelength reference is a compact portable device with a size of 18×12×6 cm. It comprises the

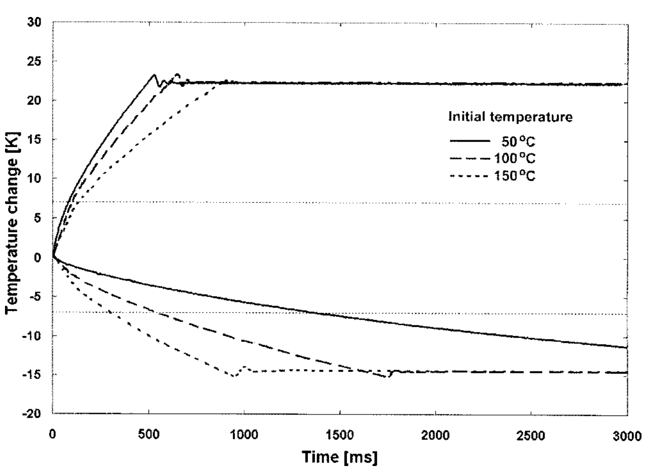


FIG. 2. Speed of temperature tuning measured for three different operating temperatures.

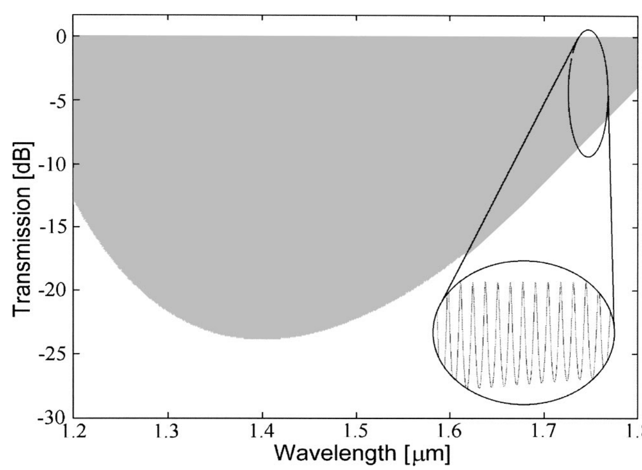


FIG. 4. Simulation of the broadband transmission of the etalon to evaluate the performance of the dielectric mirrors.

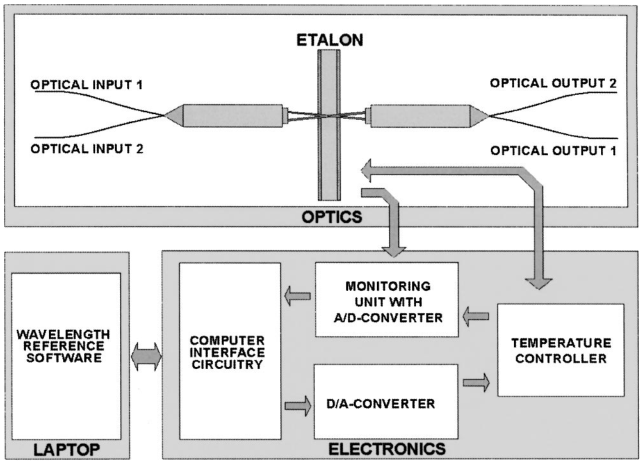


FIG. 5. Schematic diagram of the operating principle of the wavelength reference.

etalon inserted in an air gap formed between two twin-beam fiber-optic collimators, the electronics needed to tune and temperature stabilize the etalon and the necessary circuitry to provide a two-way connection to a portable computer. Twin-beam collimators were utilized to give the device more versatility. The two channels can be used either totally independently or by passing the light twice through the etalon to further reduce the bandwidth of the fringes. The attenuation of the etalon collimating system was measured to be 1.4 dB. The device can be operated, tuned, and have its parameters monitored using the computer interface and software. The temperature dependence of the refractive index of silicon is utilized in the tuning of the etalon. By applying an electronic feedback from the sensing to the heating resistor, the temperature of the chip can be both tuned and also stabilized to a value ranging from the ambient temperature to near 500 K. The temperature is controlled with a 16-bit digital-to-analog converter. It provides stabilization of the temperature to $2^{16}$ discrete values in intervals of 3.2 mK, each of these corresponding to a shift of 0.2 pm in the transmission spectrum of the etalon. The shift of the center wavelength of a fringe, $\lambda_0$, due to the temperature coefficient of the refractive index of silicon and the thermal expansion, can be calculated from

$$\frac{d\lambda_0}{dT}=\lambda_0\left(\frac{1}{n}\frac{dn}{dT}+\beta\right), \tag{3}$$

where $dn/dT$ is the temperature dependence of the refractive index and $\beta$ denotes the thermal expansion coefficient of silicon. The temperature dependence of the center frequency of a fringe is 71 pm/K. This means that a temperature change of 13.6 K is needed to shift the transmission spectrum one full FSR in the 1.55 $\mu$m region. Hence, one of the fringes can be tuned to a selected wavelength with a maximum tuning of 6.8 K to either a higher or to a lower value with respect to any reference temperature. A block diagram of the operation of the device is presented in Fig. 5. To attain the highest possible accuracy and predictability, the offsets and the linearities of the gains of the various amplifiers were measured in detail. These error sources are countered for by the controlling software.

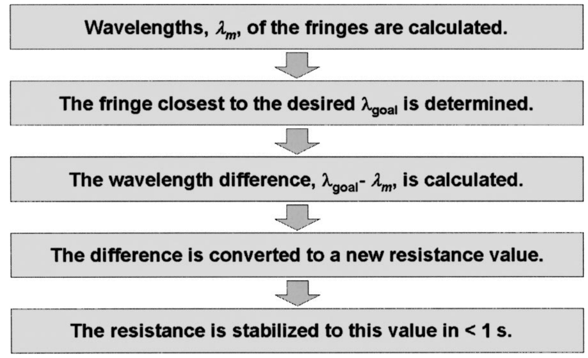


FIG. 6. Sequence of operations carried out by the software when the desired wavelength is reset.

A sequence of operations are performed whenever a new wavelength is typed in for the device. This sequence is presented in Fig. 6. The center wavelengths of the fringes are calculated utilizing the values for the thickness and the temperature of the etalon. For these calculations, each fringe should be associated with its correct mode number. After the locations of the fringes are calculated at a chosen reference temperature, the fringe closest to the selected wavelength value is determined. Subsequently, the needed change in the refractive index for tuning the fringe to the selected wavelength is calculated. This change of the refractive index of silicon is then converted to a temperature change, which is converted to a new value of the resistance for the temperature-sensing resistor. After a tuning period of 1 s at maximum, the temperature of the etalon has stabilized and a fringe is centered at the desired wavelength.

To perform the needed calculations and offer an informative and easy-to-use user interface, the reference was made computer controlled. The computer interface can also be used to record and monitor the parameters including the heating power and the temperature of the etalon. These data are useful in the investigation of the performance of the wavelength reference.

## IV. MEASUREMENT RESULTS

Beat measurements between two tunable external cavity lasers (Photonetics Tunics PRI) were carried out to estimate the performance of the wavelength reference in the important C band (1530 nm–1565 nm). The absorption spectrum of acetylene ($^{13}C_2H_2$) was selected for the measurement. It gives an absolute reference with thoroughly investigated[12,13] absorption lines ranging from 1520 nm to 1555 nm. One laser was locked to an acetylene absorption line after which the wavelength reference was set to a value 700 MHz above the absorption line. Subsequently, the second laser was locked to the center of the fringe and the beat frequency was measured with a fast photodetector and a frequency counter. Any deviation from the expected beat frequency of 700 MHz was noted as an inaccuracy of the device. The measurement was repeated for over 50 absorption lines over a range of 30 nm utilizing mode numbers in the range from 1702 to 1737. The measured frequency differences are shown in Fig. 7. All

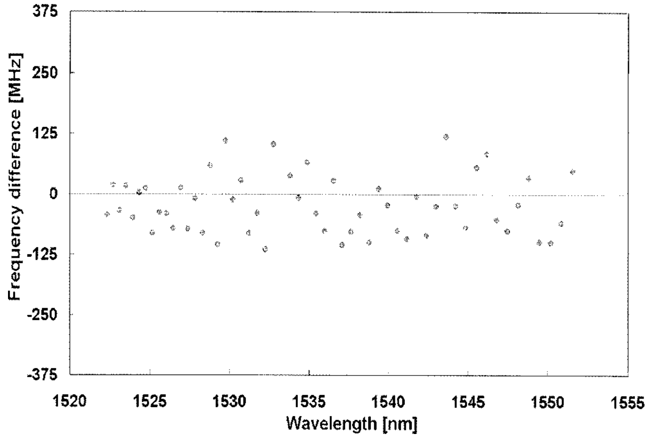


FIG. 7. Results of the laser-beat measurements to evaluate the performance of the wavelength reference at the 1.55 $\mu$m region.

of the measurement points lie within $\pm$120 MHz giving an indication of the level of performance of the device to be ~1 pm.

The short-term frequency stability was investigated by locking the output frequency of a laser to an acetylene absorption line and tuning the steepest point of the slope of a fringe of the etalon to match the center frequency of the laser. The transmission of the etalon was monitored over a time period of 40 h. The frequency drift was calculated from the variations of the transmission and was found to be smaller than 100 MHz as shown in Fig. 8. The long-term stability and the need for recalibration is governed by thermal aging effects of the temperature-sensing resistor. If aging is a limitation, the resistor can be deposited under the mirror layers or the entire etalon can be installed in a hermetically sealed package together with the collimators to prevent oxidization. The possible long-term aging effects of the control electronics can be dealt with by employing simple automated voltage-level calibrations.

The tolerance of the wavelength reference against variations in the ambient temperature was investigated using a thermal chamber. The dependence of the reference wavelength to ambient temperature was measured to be 33 fm/K. Furthermore, the device was found to be virtually immune to mechanical movement and vibration which makes it ideal for calibrations in the field.

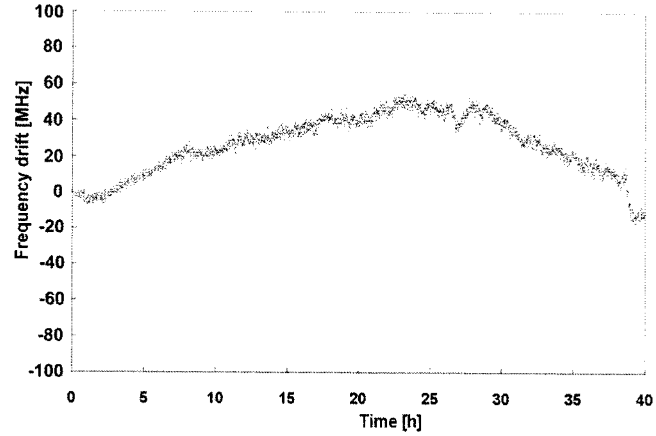


FIG. 8. Measured drift of the wavelength reference.

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