COMPACT WAVELENGTH REFERENCE FOR OPTICAL TELECOMMUNICATION BASED ON A TUNABLE SILICON ETALON

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Abstract

A wavelength reference based on a temperature-tunable etalon made from silicon is presented. The device provides a compact and cost-effective solution. Furthermore, it is fully automated and operational in a broad wavelength range from 1.3 µm to 1.7 µm. The device needs a single characterization and operates without an absolute wavelength reference. The wavelength accuracy is found to be better than 1 pm in the 1.55 µm region.

Introduction

Wavelength standards in the 1.31 µm and 1.55 µm regions are important for the present and future optical communication schemes involving wavelength division multiplexing. High accuracy will be required of these references when the channel spacing in the communication systems is decreased to 50 GHz or even 25 GHz. Such references can also be used to calibrate optical spectrum analyzers in these wavelength regions.

Stable optical resonators are widely used as wavelength and frequency references. A reference artefact based on a Fabry-Perot etalon is in contrast to atomic or molecular references uniformly applicable to a broad spectral range. In the near infrared region a solid etalon made of silicon offers many attractive features for realizing such a resonator in a compact and cost-effective format. Silicon is transparent for wavelengths in the range of 1.1 µm to 4 µm. The optical thickness of the etalon may conveniently be controlled by changing the index of refraction by temperature tuning [1]. Furthermore, the processing techniques of silicon are well developed.

We have built a wavelength reference based on a temperature-tunable Fabry-Perot etalon. The transmission spectrum of the etalon exhibits periodic transmission fringes, which can be employed as a wavelength reference once the properties of the etalon (thickness, refractive index) are determined. These values are obtained by performing a single calibration. The device can then be operated with a laptop computer without the need of frequent calibrations.

Characteristics of the tunable silicon etalon

We have recently developed a Fabry-Perot etalon, which is fabricated by depositing three pairs of dielectric quarter-wave mirrors on both sides of a double-side polished silicon wafer with a standard thickness of 380 µm [2]. Silicon dioxide and silicon nitride were used as the materials for the multilayer coatings since they have high transmission at the wavelengths of interest. The free spectral range (*FSR*) and the reflectivity (*R*) of the mirrors were determined by fitting an Airy-function to the measured transmission spectrum. The *FSR* is 110 GHz and *R* is 0.66 at a nominal wavelength of 1.55 µm. The size of the etalon chip is 10x6 mm. To control the temperature of the silicon chip two thin-film resistors were deposited on its surface concentrically in an omega-shaped pattern. These resistors can be seen in Fig. 1. The heating and temperature sensing resistors were made of molybdenum to obtain a good thermal contact with silicon. At room temperature, the resistance of the temperature sensor is 1.6 kΩ and the resistance of the heater is 35 Ω.

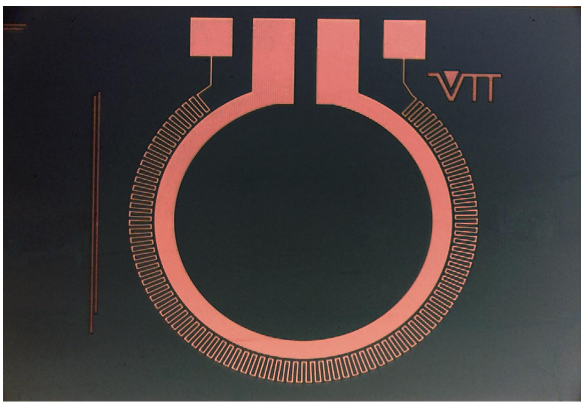

Fig. 1. Heating and sensing resistors of the etalon

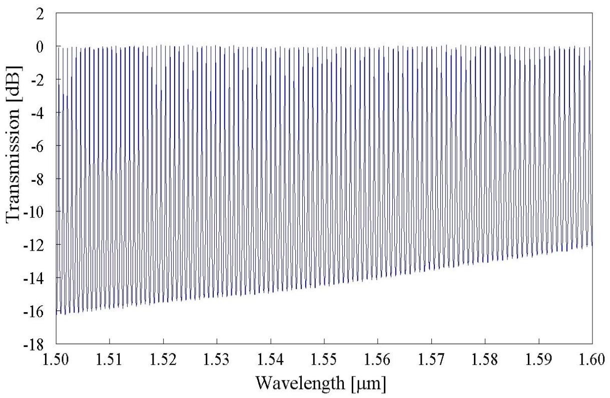

Fig. 2. Measured transmission spectrum of the etalon

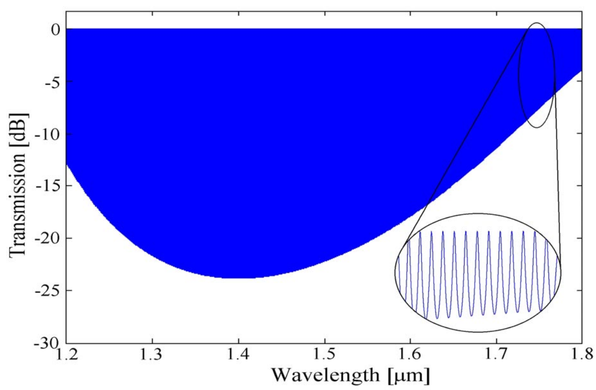

Fig. 3. Simulated transmission spectrum of the etalon

The measured transmission spectrum of the etalon from 1.5 μm to 1.6 μm is presented in Fig. 2. Due to the wavelength selectivity of the mirrors, the visibility of the fringes is increasing towards the shorter wavelengths. This indicates that the mirrors have their highest reflectivity close to 1.4 μm. To understand the properties of the etalon and its mirrors on a broader wavelength scale a simulation was performed. Again three layer-pairs of silicon dioxide and silicon nitride were implemented in the model for both sides of the etalon to form the dielectric mirrors. The layer thicknesses of the mirrors were optimized to provide the highest reflectivity at 1.4 μm. The simulation of the etalon transmission spectrum is presented in Fig. 3. Below 1.2 μm and above 1.7 μm, the reflectivity of the mirrors is decreased drastically resulting in a large bandwidth and reduced visibility of the fringes. This leads to an impaired accuracy of the reference and sets the operational range of the wavelength reference.

The refractive index of silicon exhibits a dependence on both the temperature and the wavelength and therefore an accurate model for it should be employed. The refractive index can be modeled by

$$n_{si} = 3.41696 + \frac{0.138497}{(\lambda^2 - 0.028)} + \frac{0.013924}{(\lambda^2 - 0.028)^2} - 2.09\cdot 10^{-5}\lambda^2 + 1.48\cdot 10^{-7}\lambda^4 + dn\cdot(T - T_0), \quad (1)$$

where dn is the temperature coefficient of silicon with a value of $1.5\cdot 10^{-4}$ 1/K, T_0 is the ambient temperature of 293 K, T is the temperature of the silicon chip in Kelvins and λ is the wavelength in micrometers [3]. The length of the cavity is affected by the refractive index of silicon, the multilayer mirrors, thermal expansion and the angle of incidence. These have to be accounted for in the calculations to ensure good accuracy over a broad wavelength span.

The wavelength reference

The wavelength reference is an enclosure with a size of 18x12x6 cm connected to a computer via its parallel port. The enclosure comprises the etalon inserted in an air gap formed between two fiber-optic collimators, and the electronics needed to tune and temperature stabilize the etalon. The wavelength reference can be tuned and its parameters monitored with the computer interface. The temperature dependence of the refractive index 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 up to about 480 K. The temperature is controlled with a 16-bit digital-to-analog converter. It provides stabilization of the temperature to 65535 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 frequency of a fringe, ν_0, due to the temperature coefficient of the refractive index of silicon and the thermal expansion can be calculated from

$$\frac{d\nu_0}{dT} = -\nu_0\left(\frac{1}{n}\frac{dn}{dT} + \beta\right), \quad (2)$$

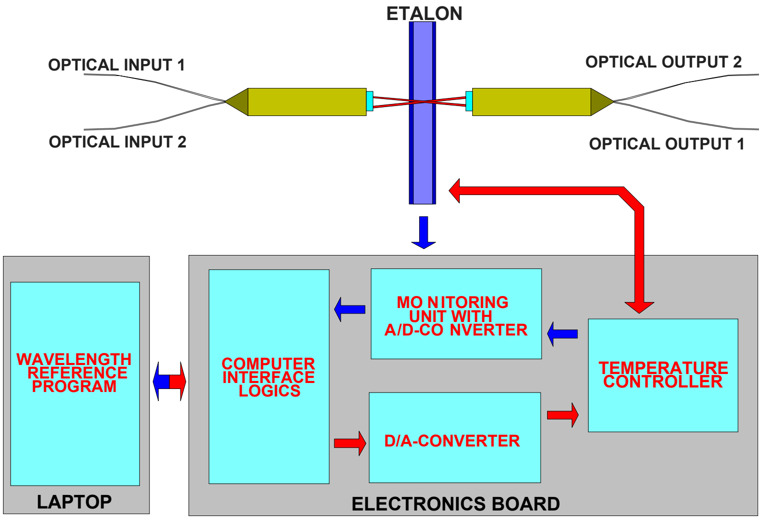

Fig. 4. Block diagram of the wavelength reference

where *dn/dT* is the temperature dependence of the refractive index and β is the thermal expansion coefficient of silicon. The temperature dependence of the center frequency of a fringe is 8.1 GHz/K. This means that a temperature change of 13.6 K is needed to shift the transmission spectrum one full *FSR*. 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. In Fig. 4, a block diagram is presented to illustrate the operation of the device. The converters and the instrumentation amplifiers do not have a completely linear output. These nonlinearities are measured and taken into account in the computer program.

When the wavelength reference is requested to tune to a selected wavelength, a sequence of operations are performed. 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 reference temperature, the fringe closest to the selected wavelength value is determined. Subsequently, the change in the refractive index needed for tuning the fringe to a selected wavelength is calculated. This change 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 about 200 ms, the temperature of the etalon has stabilized and a fringe is centered at the desired wavelength.

The reference is operated with a computer program to minimize the number of electronic components needed. The program is designed to perform the calculations and offer an easy-to-use user interface. The computer interface can also be used to record and monitor the parameters including the heating power and the temperature of the etalon. This data is useful in the investigation of the performance of the wavelength reference.

Measurements

To estimate the frequency stability and accuracy of the wavelength reference, beat measurements between two external cavity lasers were carried out. The output frequency of one tunable laser (Photonetics Tunics PRI) was locked to the peak of a transmission fringe of the etalon. Another similar laser was locked to an absorption line of acetylene to have an accurate reference [4]. The wavelength reference was operated so that the frequency of a fringe was offset by 700 MHz with respect to the frequency of the absorption line. The beat frequency was measured with a fast photodectector and a pulse counter. The measurement was repeated for 54 absorption lines of acetylene over a range of 30 nm in the 1.55 µm region. The measured frequency differences are shown in Fig. 4. The expected beat frequency of 700 MHz is marked by a horizontal line. All of the measurement points lie within ±120 MHz indicating the wavelength accuracy of the device to be better than ±1 pm.

The 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 hours. The frequency drift was calculated from the variations of the transmission and was found to be smaller than 100 MHz as shown in Fig. 5.

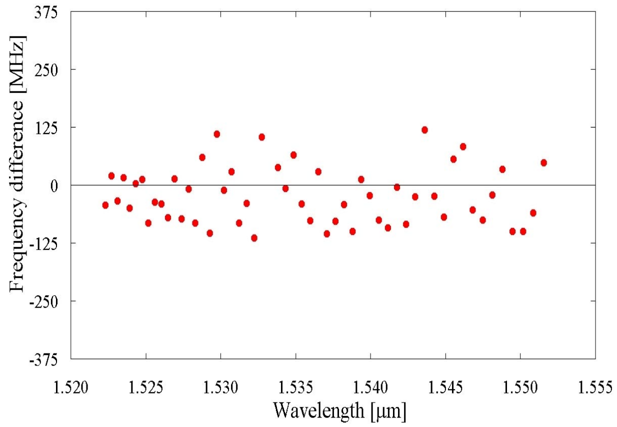

Fig. 4. Measured frequency difference

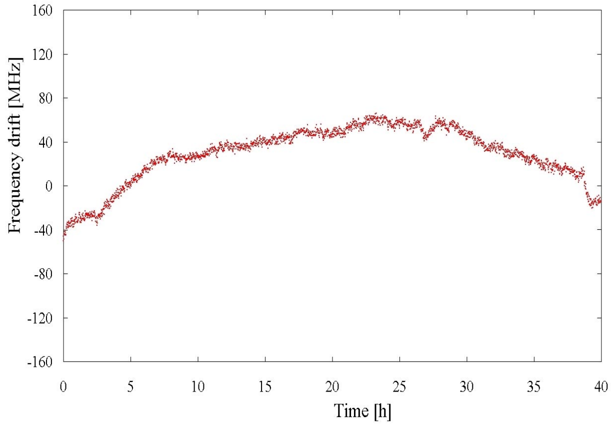

Fig. 5. Frequency stability measurement

Conclusion

We have developed a compact and cost-effective wavelength reference for calibration of the wavelength scale of various optical measurement instruments. The reference is fully automated and it can easily be configured to provide a reference for any wavelength over a bandwidth of 500 nm. Furthermore, it is robust against mechanical and environmental perturbations making it well suited for field use. The accuracy of the reference was estimated in the 1.55 μm region by performing beat measurements. Preliminary results demonstrate an accuracy of the artifact on the order of 1 pm, which is adequate for various calibration purposes.

Acknowledgments

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