Tunable Three-Dimensional Solid Fabry–Perot Etalons Fabricated by Surface-Micromachining

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***Abstract*—We report on novel tunable three-dimensional solid Fabry–Perot etalons fabricated by the surface-micromachining technique. The Fabry–Perot etalon is monolithically integrated with an on-chip rotation stage for angle tuning. A wavelength tuning range of 45 nm has been achieved at 1.3 μm wavelength for a rotation angle of 70°. The optical properties of the polysilicon materials have also been characterized using the etalon as testing vehicles.**

I. Introduction

WAVELENGTH-division multiplexing (WDM) is an attractive approach to increase the bandwidth and routing capability of optical networks. Broadband tunable Fabry–Perot etalons are desired in WDM systems as wavelength demultiplexers. Various approaches have been proposed to enhance the integrability of Fabry–Perot etalons. For example, the FiEnd etalon filters invented at AT&T Bell Laboratories eliminate fiber pigtailing problems by forming mirrors directly on the cleaved ends of expanded-core fibers [1]. By employing photolithographic technique, micromachined Fabry–Perot interferometer with a corrugated silicon diaphragm support [2] and tunable micromachined gallium arsenide Fabry–Perot filters [3] have been realized. However, most of the microfabricated Fabry–Perot filters developed to date are restricted to the surface of substrate with light incident from the surface-normal direction, which makes fiber-to-fiber coupling more difficult. The integrability with other micro-optical elements is also limited.

The surface micromachining technique offers a new approach to implement three-dimensional free-space micro-optics monolithically. Previously, we have proposed a "*Free-Space Micro-Optical Bench* (FS-MOB)" technology for optoelectronic packaging and free-space integrated optics [4], [5]. On the micro-optical bench, various three-dimensional micro-optical elements such as micro-lenses [4], mirrors [4]–[6] and gratings [7] can be fabricated integrally on a single silicon chip by the surface-micromachining technique. In this paper, we report on the first fabrication of novel three-dimensional tunable solid Fabry–Perot etalons monolithically integrated with rotation stages using the FS-MOB technology. Very broad tuning range (45 nm) is achieved using the on-chip rotation stage. The polysilicon solid etalon also provides an ideal testing vehicle for characterizing of the optical properties of the micromachined polysilicon plates.

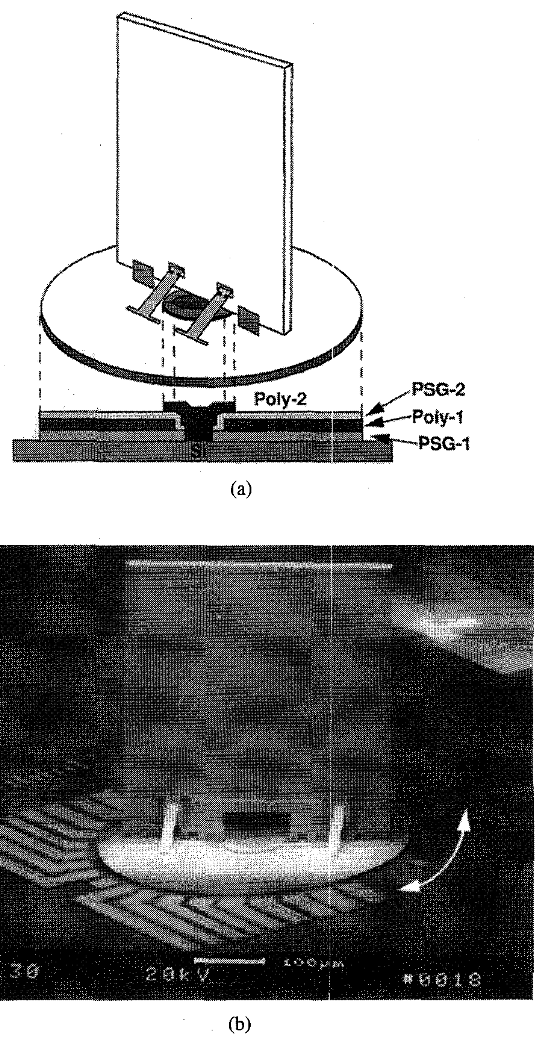

Fig. 1. (a) The schematic drawing and (b) SEM micrograph of the solid Fabry–Perot etalon integrated with a rotation stage.

Fig. 1(a) shows the schematic diagram of the tunable Fabry–Perot etalon. It consists of a solid etalon and a rotation stage. The etalon is made to stand perpendicular to the substrate so that it can be integrated with other optical compo-

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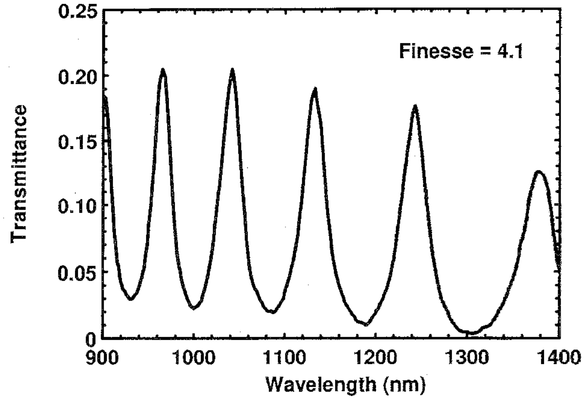

Fig. 2. The transmission spectrum of the three-dimensional solid Fabry–Perot etalon with 300-Å-thick Au coating on one side at normal incidence.

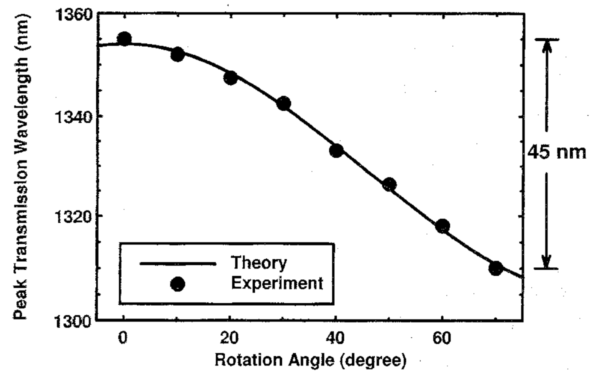

Fig. 3. The peak transmission wavelength of the three-dimensional Fabry–Perot etalon versus the rotation angle of the on-chip rotation stage.

nents. For example, the etalon can be cascaded with another etalon with different free-spectral range to optimize the filter bandwidth; or it can be integrated with bulk-micromachined V-grooves for aligning input and output optical fibers. The three-dimensional etalon and the rotation stage are fabricated integrally using the surface-micromachining technology. The fabrication processes have been described in detail in [4]. One side of the polysilicon etalon is coated with a thin layer of Au to increase its reflectivity. The polysilicon etalon is rotated out of the substrate plane after fabrication and releasing, and held by the micro-hinges and micro-spring latches [8]. The structure of the rotation stage itself is similar to that of the micromotors [9]. The Fabry–Perot etalon can be angle-tuned by rotating the integrated stage. Fig. 1(b) shows the scanning electron micrograph (SEM) of an assembled solid Fabry–Perot etalon integrated with a rotation stage that has been rotated by about 45°. The etalon is 1.48 μm thick, and has dimensions of 400 μm by 400 μm.

The transmission characteristics of the tunable etalon is characterized using a white light source and an optical spectrum analyzer. Fig. 2 shows the transmission spectrum of the solid Fabry–Perot etalon coated with 300 Å-thick Au at normal incidence. The low transmission intensity comes mainly from the optical loss through the Au film. The finesse of the etalon is found to be 4.1 from the measurement data. By rotating the Fabry–Perot etalon, the peak transmission wavelength changes according to the following relation

$$\lambda_P = \lambda_0 \cdot \sqrt{1 - \left(\frac{\sin\theta_i}{n_{\text{poly}}}\right)^2}, \tag{1}$$

where λ_0 is the peak transmission wavelength at normal incidence, θ_i is the incident angle of the light source with respect to the normal direction of the etalon, and n_{poly} is the refractive index of the polysilicon plate (material of the solid etalon). Fig. 3 shows the change of the peak transmission wavelength versus the tuning angle. A tuning range of 45 nm is achieved by rotating the Fabry–Perot etalon over 70°. The refractive index of the polysilicon plate can be extracted by fitting the experimental peak wavelength with (1). A value of $n_{\text{poly}} = 3.75$ is obtained, which is in between of the refractive indices of single crystalline silicon and amorphous silicon at this wavelength.

Since polysilicon is the most commonly used material in surface micromachining, it is important to characterize its optical properties. The solid etalon constructed in our experiment provides an ideal testing vehicle. By analyzing the transmission spectrum of an uncoated etalon, the optical loss of the polysilicon plate can be characterized [10]. Fig. 4 shows the optical loss per pass as a function of the wavelength. The loss consists of two components: a fast decaying component for wavelength shorter than 1.1 μm, and a slowly varying component at long wavelength. The fast decaying is dominated by the optical absorption above bandgap. For wavelength longer than 1.1 μm, the optical loss approaches a loss floor of 7.9% per pass. This loss includes the scattering loss at the polysilicon/air interface, diffraction loss, and the residue below-bandgap absorption loss of polycrystalline materials. The dominant loss is attributed to the scattering loss due to the granular surface of the polysilicon plate formed during the deposition process. The mirror reflectivity of the Au coated etalon can also be analyzed from its transmission spectrum [10]. From the transmission spectrum shown in Fig. 2, the intensity reflectivity of polysilicon–Au–air interface (from the polysilicon side) is estimated to vary from 60% for $\lambda = 950$ nm to 86% for $\lambda = 1400$ nm, which is in good agreement with the data calculated from the complex refractive index of the Au film [11]. The finesse of the etalon can be increased by applying high-reflection (HR) dielectric coating. Fig. 5 shows the transmission spectrum of a solid Fabry–Perot etalon coated with three pairs of SiO_2–Si quarter wavelength dielectric mirrors on both sides, with light incident at 50°. The finesse is increased to 11. The transmittance, however, becomes lower because that the intensity loss within the polysilicon plate now contributes more significantly as the reflectivity increases. The finesse can be further increased by polishing the surface of the polysilicon plates using chemical-mechanical polishing [12] to reduce the scattering loss, or using the silicon on insulator (SOI) structure in the micromachining process. This type of etalon is useful for WDM systems at the communication wavelengths of 1.3 μm and 1.55 μm.

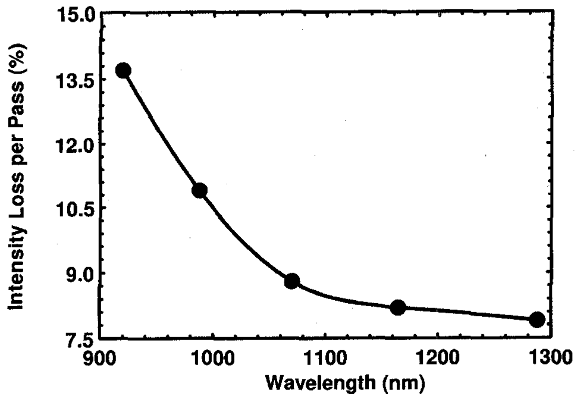

Fig. 4. Optical loss per pass versus wavelength of the solid Fabry–Perot etalon.

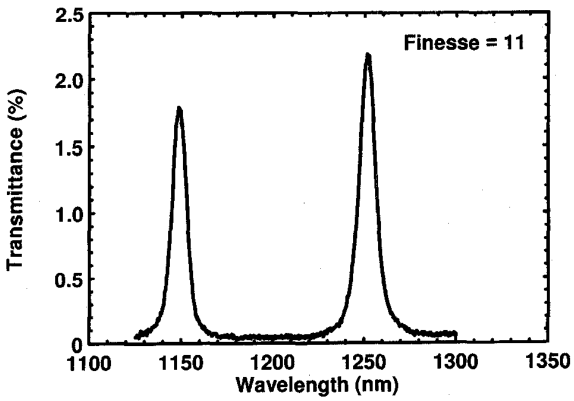

Fig. 5. The transmission spectrum of a three-dimensional solid Fabry–Perot etalon with high-reflection dielectric coating on both sides at an incident angle of 50°.

II. Summary

We have demonstrated three-dimensional tunable solid Fabry–Perot etalons fabricated integrally with rotation stages using the surface micromachining technique. A tuning ranges of 45 nm has been achieved by rotating the on-chip rotation stage over 70°. The finesse of the Au-coated etalon is 4.1. After applying high-reflection dielectric coatings, the finesse is increased to 11. The optical properties of the polysilicon materials have also been characterized using the etalon as testing vehicles. The three-dimensional Fabry–Perot etalons can be integrated with other free-space micro-optical elements fabricated by similar technique, and have applications in wavelength-division multiplexing systems and optical sensors.

Acknowledgment

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References

[1] J. Stone, L. W. Stulz, D. Marcuse, C. A. Burrus, and J. C. Centanni, "Narrow-band FiEnd etalon filters using expanded-core fibers," *IEEE J. Lightwave Technol.*, vol. 10, no. 12, pp. 1851–1854, 1992.

[2] J. H. Jerman, D. J. Clift, and S. R. Mallinson, "A miniature Fabry–Perot interferometer with a corrugated silicon diaphragm support," *Sensors and Actuators A*, vol. 29, pp. 151–158, 1991.

[3] E. C. Vail, M. S. Wu, G. S. Li, L. Eng, and C. J. Chang-Hasnain, "GaAs micromachined widely tunable Fabry–Perot filters," *Electron. Lett.*, vol. 31, no. 3, pp. 228–229, 1995.

[4] L. Y. Lin, S. S. Lee, K. S. J. Pister, and M. C. Wu, "Micro-machined three-dimensional micro-optics for integrated free-space optical system," *IEEE Photon. Technol. Lett.*, vol. 6, no. 12, pp. 1445–1447, 1994.

[5] M. C. Wu, L. Y. Lin, and S. S. Lee, "Micromachined free-space integrated optics," in *Proc. SPIE, Integrat. Opt. and Microstructures II*, 1994, vol. 2291, pp. 40–51.

[6] O. Solgaard, M. Daneman, N. C. Tien, A. Friedberger, R. S. Muller, and K. Y. Lau, "Optoelectronic packaging using silicon surface-micromachined alignment mirrors," *IEEE Photon. Technol. Lett.*, vol. 7, no. 1, pp. 41–43, 1995.

[7] S. S. Lee, L. Y. Lin, and M. C. Wu, "Surface-micromachined free-space micro-optical systems containing three-dimensional micro-gratings," *Appl. Phys. Lett.*, vol. 67, , no. 15, pp. 2135–2137, 1995.

[8] K. S. J. Pister, M. W. Judy, S. R. Burgett, and R. S. Fearing, "Microfabricated hinges," *Sensors and Actuators A*, vol. 33, pp. 249–256, 1992.

[9] L. S. Fan, Y. C. Tai, and R. S. Muller, "IC-processed electrostatic micromotors," *Sensors and Actuators*, vol. 20, pp. 41–47, 1989.

[10] A. Yariv, *Optical Electronics*, 4th ed. Orlando, FL: Saunders College Publishing, 1991.

[11] A. J. Moses, "Refractive index of optical materials in the infrared region," Culver City, CA, Electronic Properties Information Center, Hughes Aircraft Co., 1970, pp. 8–14.

[12] A. A. Yasseen, S. W. Smith, M. Mehregany, and F. L. Merat, "Diffraction grating scanners using polysilicon micromotors," in *Proc. 1995 IEEE Micro Electro Mechanical Syst.*, Amsterdam, The Netherlands, Jan. 1995, p. 175.