Tunable Thin Film Filters Using Thermo-Optic Silicon

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Abstract: Thin film tunable filters without moving parts use thermo-optic effects in PECVD amorphous silicon. Demonstrations include single and multiple cavity tunable filters, and fixed wavelength switchable WDM add/drop filters using hybrid dielectric / semiconductor cavities.

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1. Tunable thin films

It is notable that thin film interference filters, the most widely deployed type of static fixed WDM filter, to date have not had a tunable counterpart except for limited application of mechanically rotated filters. Recent studies of non-mechanically tunable thin films have explored electro-optic or piezo-electric effects, or thermo-optic effects in dielectrics, but have not yielded wide tunability, acceptable insertion loss, or low voltage operation [1,2]. The family of tunable thin film components described here is based on the incorporation of amorphous silicon and its alloys, which until now have seen little use in thin film coatings for telecommunications applications. Although amorphous silicon has a large index and small near-IR absorptance, it is known to be temperature sensitive and therefore has generally been considered unsuitable for use in passive WDM components where stability is a primary requirement. We have reversed this logic and sought to develop components with maximum thermo-optic tunability [3,4,5]. In addition to tunable single and multi-cavity filters, we describe a second type of device based on hybrid combinations of a thermo-optically tunable semiconductor cavity with multiple cavities of non-tunable dielectric materials, to make hybrid filters that are fixed in wavelength but may be thermally switched between transmissive and reflective states.

2. Thermo-optic tuning of amorphous silicon

PECVD is a flexible and homogeneous thin film process for the production of hydrogenated amorphous silicon (a-Si:H), yielding low absorptance in the WDM band at 1500 nm with a value 0.4 cm^{-1} corresponding to extinction coefficient $k=4\mathrm{X}10^{-6}$, comparable to low loss dielectric materials commonly used in conventional thin film WDM filters [6]. Films of a-Si:H deposited by PECVD also display large thermo-optic coefficients, ranging from $dn/dT = 2.3 \times 10^{-4}$ / K at 300K to 2.9×10^{-4}/°C at 480K as measured by Della Corte and others, values five to ten times larger than for dielectric materials such as Ta_2O_5 and SiO_2 conventionally used in WDM filters [7]. Cocorullo and coworkers have demonstrated both guided wave and expanded beam tunable components using the thermo-optic properties of thin silicon wafers, and also the use of amorphous silicon films in waveguides [8]. As a low index companion material, silicon nitride is readily produced by PECVD, and by control of gas ratios can be varied in composition from stoichiometric Si_3N_4 to nonstoichiometric to alter not only the index but also the film stress over a wide range of tensile and even compressive values, a flexibility not available with low index oxides. While amorphous silicon layers in Fabry-Perot cavities and mirror stacks provide large thermo-optic coefficients, large temperature changes >300°C are also necessary to achieve tuning over the telecom C band (35 nm). Reliable operation with repeated cycling over such large temperature changes in microscopic volumes without delamination, bubbling or cracking requires engineering of film stresses and thermal conductivities, CTE matched substrates, and the development of annealing recipes to stabilize structures. Thin film devices have now been developed which combine telecom-grade reliability with index modulations as large as 4%, offering wide tunability and flexibility of optical design. Typical tuning speeds are on the order of a few milliseconds.

3. Tunable single and dual cavity filters

Figure 1 shows the transmission spectrum of a single cavity amorphous silicon/silicon nitride filter on a Si wafer substrate with formula $\{\text{substrate} \mid (HL)^6\ 4H\ (LH)^6 \mid \text{air}\}$, where H=quarter wave film of a-Si:H and L=quarter wave film of a-SiNx, at two temperatures, 25°C and 125°C. The insertion loss is -4.1 to -4.8 dB and the -3dB width 190 pm and the coefficient of thermal tunability in this example is 96 pm/°C. Figure 2 shows the center wavelength as a function of temperature for a device heated by an internal resistive film of doped polysilicon, with a change of 37 nm over 25-325°C for a mean rate of 123 pm/°C.

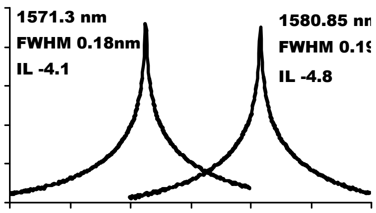

Figure 1. Single cavity filter at temperatures 25C and 125C.

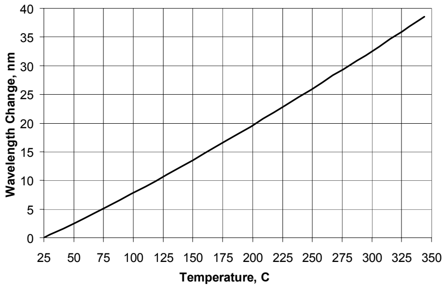

Figure 2. Center wavelength change vs. temperature

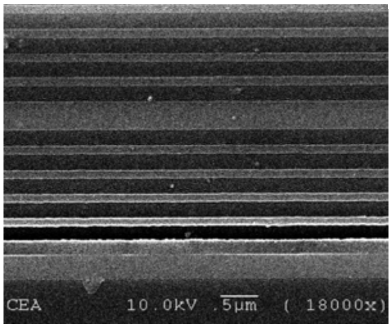

Figure 3. Scanning electron microscope image of a sectioned filter. Dark regions are a-SiNx, lighter regions are a-Si:H.

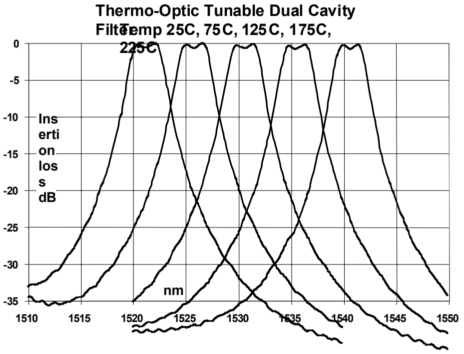

Figure 4. Temperature scanning of dual cavity filter 25-225C.

Studies of a variety of devices with different structures and annealing conditions show dλ/dT values ranging from 85 pm/°C near room temperature to 172 pm/°C at 400°C. This is to be compared with the thermal coefficient 14 pm/°C of a typical Fabry-Perot filter using tantalum pentoxide and silicon dioxide on a fused silica substrate as described by Takashashi [9]. Packaged devices require an integrated, electrically conductive heater; Figure 3 shows a scanning electron micrograph of a sectioned film stack deposited on a fused silica substrate with polysilicon heater.

3. Multicavity filters

Figure 4 shows the transmission versus temperature for a simple dual cavity filter with the formula $\{S \mid (HL)^3\ 4H\ (LH)^3\ L\ (HL)^3\ 4H\ (LH)^3 \mid \text{air}\}$ on a fused silica substrate over the range 25-225°C. It is notable that neither the insertion loss -0.5 dB nor the band pass shape vary significantly over this temperature range, showing that the matching of cavity optical thicknesses of one part in 10^4 achieved during deposition is maintained as the filter is heated, demonstrating the feasibility of thermo-optic multicavity designs. The coefficent of thermal tuning of center wavelength is 95 pm/°C, similar to single cavity filters.

4. Switchable add/drop filter

Whereas single cavity silicon-based thermo-optic filters are tunable in wavelength, the functionality can be extended by combining non-tunable dielectric films with tunable semiconductor films. Hybrids of this type display modes of operation quite different from simple wavelength tunability. The switchable add/drop filter described here is fixed in wavelength but transitions continuously between transmission and reflection by means of temperature change.

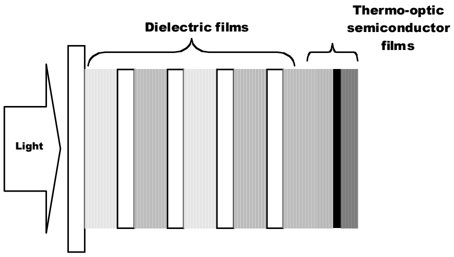

Figure 5. Switchable thin film filter based on combination of dielectric films and thermo-optic semiconductor films.

Figure 6. Transmission and reflection at the fixed wavelength 1548.3 nm as a function of temperature.

The principle of operation may be understood from Figure 5 which shows schematically a five cavity filter designed for narrowband transmission at a selected wavelength channel. Four matched cavities forming the base portion of the filter are deposited using conventional dielectric thin film high/low index combinations which display very small thermo-optic coefficients. On top of this structure, a final, fifth, thermally sensitive, cavity is deposited by PECVD. The fifth spacer thickness is deposited such that at room temperature its resonant wavelength is a few nm below that of the underlying four passive cavities, with the result that filter is almost totally reflective (non-transmissive) at the design channel. As the temperature of the device is increased, a 'resonant temperature' is reached where the fifth cavity becomes phase matched to the group of four. To realize this structure, a four cavity structure was deposited on a white crown glass substrate by ion-assisted e-beam evaporation using Ta_2O_5 and SiO_2. This portion of the filter has 104 layers and a center wavelength 1548.3 nm at 25°C and, considered by itself, a thermo-optic tuning coefficient 0.001 nm/°C. A fifth cavity was then deposited by PECVD using thermo-optic a-Si:H and non-stoichimetric silicon nitride for an additional 13 layers, with a thermal tuning coefficient 0.10 nm/°C. The silicon cavity was targeted with a center wavelength of 1545.8 nm, so that a temperature increase of approximately 25-30°C would bring it into resonance with the existing cavities. As expected, at room temperature 25°C the resulting mismatched filter stack had very little transmission at any wavelength in the C band; at 49°C, the 'resonant temperature,' the transmission was maximized, the band pass shape optimized, and the reflectivity minimized . Figure 6 shows the transmissivity and reflectivity at 1548.3 nm as a continuous function of temperature.

5. References

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