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Tunable thin film filters

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Abstract

We report widely tunable thin film filters, including both single-cavity and multi-cavity designs, based on thermo-optic effects in thin films of amorphous semiconductors deposited by PECVD. Applications include an optical channel monitor packaged in a TO can.

1. Thermo-optically tunable thin films

Requirements for tunable components, not only tunable filters but also other wavelength management and control devices, are increasingly important in WDM network architectures. Several tunable technologies have emerged, including MEMS, stretched fiber Bragg gratings, and acousto-optic and liquid crystal devices. All techniques of tunability are either mechanical or else rely on modulation of refractive index in some optical material. It is notable that thin film interference filters, the most widely deployed type of static fixed WDM filter, have not had a tunable counterpart except for limited application of mechanically rotated or translated filters. Previous attempts at tunable thin films based on index control, based for the most part on electro-optic or piezo-electric effects, have not yielded wide tunability, acceptable insertion loss, or low voltage operation [1].

The tunable thin film filters described here are based on the large thermo-optic coefficients $3.6\mathrm{X}10^{-4}$/K in thin films of amorphous Si deposited by PECVD (plasma enhanced chemical vapor deposition). Using hydrogenation and optimized process control, films of a-Si:H have been developed with very low loss in the near IR and robust film-to-film and film-to-substrate adhesion, leading to tunable thin film filters with finesse up to 4,500, tuning range up to 60 nm, and 10 ms tuning times with 5 V operation.

Amorphous semiconductors, developed over many years primarily by the flat-panel display and solar cell industries, are less familiar in the photonics and fiber optic device communities. They can be deposited as thin films by various PVD or CVD techniques. PECVD is a particularly flexible and homogeneous thin film process, and control of the basic deposition parameters such as plasma power, total gas pressure, hydrogen partial pressure, gas ratios, flow rates, and substrate temperature can be used to significantly modify film density and stoichiometry which in turn influence index, optical absorptivity, and thermo-optic coefficients. Hydrogenation of the Si films decreases defect densities by quenching dangling bonds, reducing infrared absorptivity. By optimizing PECVD conditions, we have achieved a-Si:H films with thermo-optic coefficient of $dn/dT = 3.6\mathrm{X}10^{-4}$ /K and absorptivity 0.1 cm^{-1} at 1500 nm, corresponding to extinction coefficient $k=1\mathrm{X}10^{-6}$, comparable to low loss dielectric materials commonly used in conventional thin film WDM filters.

Hydrogenated amorphous silicon (a-Si:H) possesses a high index (3.6) but has not been considered a desirable material in thin film interference filters precisely because of its temperature sensitivity. By applying internal film temperatures >400C, silicon index modulations $\delta n/n=0.04$ have been observed. Using internal heater films to generate large temperature changes >400C in microscopic volumes, device tuning times are on the order of ms, sufficiently fast for a broad range of applications.

In order to achieve such large temperature excursions in thin film structures whose total thickness may be only a few micrometers, extremely robust film adhesion is a primary requirement. As a plasma based technique, PECVD offers the process controls to produce dense, compliant films of several optically distinct but chemically compatible materials, such as amorphous silicon and amorphous silicon nitride, with widely different indices. Transition between materials is accomplished by controlling gas mixtures, without breaking vacuum. In the studies reported here, thin film structures based on amorphous silicon and silicon nitride have been demonstrated to undergo repeated temperature gradients exceeding 500C without delamination or failure. Martinu et al have shown the benefits of PECVD for the physical properties of dielectric thin films, including reduced stress [2].

Using internal heater films to generate large temperature changes in microscopic volumes, we have produced single-cavity Fabry-Perot filters with up to 60 nm tuning range in the WDM 1480-1620 bands. Moreover, unlike MEMs Fabry-Perot filters, thin film interference coatings are not limited to simple, single-cavity designs. Multi-cavity filters with steep skirts and flattened passbands can be designed for applications such as tunable add-drop filters, and other complex thin film structures containing several resonant cavities are applicable to dynamic gain equalizers and tunable dispersion compensators.

2. Tunable single cavity filter

The basic device structure for a thermo-optically tunable thin film filter with five mirror periods and a two half-wave cavity is as follows

Substrate | (HL)^5 4H (LH)^5 | air

Where H= quarter wave film of a-Si:H and L=quarter wave film of a-SiNx. Also required is an electrically conductive heater film, such as n-type polysilicon, which is optically low in loss at 1500 nm, capable of precise thickness control and strong adhesion over a wide temperature range, and can be integrated into the optical design of the thin film stack. Except for the heater, the optical filter stack can then be made of only two materials, a-Si:H (n=3.67) and non-stoichiometric SiNx (n=1.77) to compose both the mirror layers and cavity. As is well known, thin film mirrors are deposited as alternating quarter wave pairs of high and low index films, and the cavity consists of an integral number of half-waves, in this case two to four. Because of the large index contrast between a-Si:H and a-SiNx, a relatively small number of mirror pairs is required. Four pairs yields reflectivity R=98.5% at the design wavelength, and five pairs yields R=99.6% Figure 1 shows a scanning electron micrograph of a sectioned film stack.

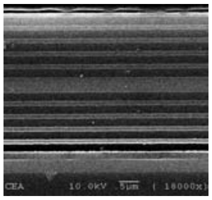

Figure 1. Scanning electron microscope image of a sectioned filter. Dark regions are a-SiNx, lighter regions are a-Si:H.

With five-period mirrors and a two half-wave cavity, the filter -3dB width is 0.55 nm and the insertion loss is -2.0 dB. Narrower filters are possible; Figure 2 shows a single cavity filter with six period mirror stacks and a four half-wave cavity, yielding a -3dB width 0.085 nm, a free spectral range of 388 nm and a finesse approximately F=4,500. Figure 3 shows the thermo-optic tunability of a filter made with all-PECVD films using amorphous silicon not only for the spacer but also for the mirror high index layers.

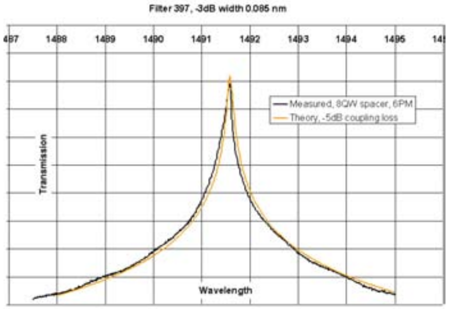

Figure 2. Single cavity filter passband compared to theory; -3dB width is 0.085 nm.

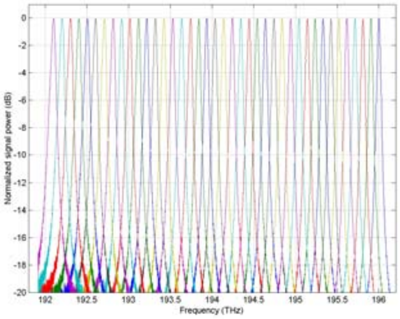

Figure 3. Tuning of thin film filter over 40 nm range.

We have observed tuning coefficients 0.08 – 0.15 nm/K by use of various spacer alloys and filter designs, and overall tuning ranges exceeding 40 nm. By comparison, conventional static thin film filter technology aims to achieve thermal variation of center wavelength < 0.0005 nm/K for narrowband WDM filters, accomplished in part through use of high CTE substrates to compensate small amounts of thermo-optic tuning. Thus the use of amorphous semiconductor films, optimized PECVD deposition, CTE matched substrates, and internal heater films to maximize thermal control, results in thermo-optic tunability approximately 300X larger than typical fixed WDM filters, without moving parts.

3. Dual cavity filters

As noted, thin film interference coatings can be designed with complex structures including multiple cavities. To demonstrate this capability, we deposited a dual cavity film stack with the formula

Substrate | (HL)^4 4H (LH)^4 L (HL)^4 4H (LH)^4 | air

Figure 4 shows the filter spectrum to be close to the theoretical prediction, with narrower skirts than a comparable single cavity filter, -3dB width 0.84 nm and insertion loss about -3.8 dB. Figure 5 shows the thermo-optic tuning of this filter over 21.4 nm by oven control of the temperature over the range 25-243C.

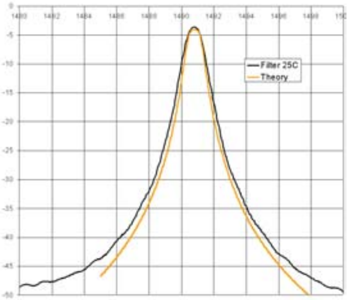

Figure 4. Dual cavity filter, compared to theory.

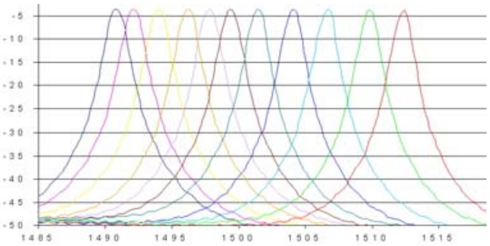

Figure 5. Tunable dual cavity filter.

4. Applications - Optical Channel Monitor

Tunable filters fabricated by this approach may be produced and tested on a wafer scale. The tunable optical device, exclusive of drive electronics, is only slightly larger than a conventional static thin film filter chip; consequently, packaging methods already well developed for mounting and fiber pigtailing of conventiona thin film filters may be applied to the tunable version with little modification. Figure 6 shows an application for an optical channel monitor in which a C band tunable filter, fiber pigtail and collimator, and detector are mounted in a low cost TO-5 can.

Figure 6. Optical channel monitor packaged in a TO-5 can.

5. References

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