

# Switchable thin film add/drop filter

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**Abstract:** A five-cavity, 117 layer, 200GHz thin film add/drop filter fabricated from combined dielectric / semiconductor materials is thermo-optically switched between transmission and reflection at a fixed channel 1548.3 nm with a contrast ratio 18.4 dB.

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## 1. Integrated switchable filters

Current commercially available switchable add/drop filters typically are modules which for each channel combine separate elements including two thin film filters, a mechanical switch and in some cases a variable optical attenuator (VOA) [1]. Wider deployment of switchable add/drops in metro networks would be enabled by a more compact, lower cost device in which the filter itself switched between add/drop and through ports, ideally with no moving parts, substantially reducing the component count. We report experimental demonstration of an extremely compact thin film filter that switches thermo-optically between transmissive and reflective states at a fixed wavelength channel. The thin film interference coating comprises five cavities, four of which are made using conventional dielectric materials and the fifth with strongly thermo-optic layers of hydrogenated amorphous silicon (a-Si:H). By temperature tuning, the several cavities can be brought into or out of resonance, switching between transmission and reflection at the fixed channel.

## 2. Thermo-optic thin film filters

We have described techniques of thermo-optically tunable thin film interference coatings based on Plasma Enhanced Chemical Vapor Deposition (PECVD) of hydrogenated amorphous silicon (a-Si:H) films together with low index companion dielectrics such as silicon nitride [2,3]. These processes were adapted from the solar cell and flat panel display industries and have only recently been introduced into photonic devices. By virtue of the high index ( $n=3.73$ ) and low absorptivity ( $k=4 \times 10^{-6}$ ) of amorphous silicon at 1500 nm and with silicon nitride as a low index companion material ( $n=1.77$ ,  $k=1 \times 10^{-6}$ ), we have demonstrated single cavity Fabry-Perot filters with -3dB widths as narrow as 0.08 nm.

Amorphous silicon also possesses an unusually large thermo-optic coefficient, ( $dn/dT > 3.6 \times 10^{-4}/^{\circ}\text{C}$ ), leading to thermal tunability coefficients of Fabry-Perot filters from 0.1 to 0.14 nm/ $^{\circ}\text{C}$  depending on operating temperature range. Full use of these large thermo-optic tunability coefficients to cover the C or L bands requires large temperature changes in microscopic volumes and hence extremely robust film adhesion and stability. PECVD is well suited to produce compliant, dense films of pairs of optically distinct but chemically compatible materials by alternating gas flows. Through optimization of plasma and gas parameters and substrate temperatures it is possible to produce a range of film densities and stoichiometries which in turn influence optical constants, adhesion and film stresses. Robust film adhesion enables filter temperature ranges exceeding 400 $^{\circ}\text{C}$  without delamination or failure, allowing the use of silicon index modulations as large as 4%. Such large dynamic index changes are virtually unique among inorganic photonic materials. On this basis tunable single cavity Fabry-Perot filters have been demonstrated with up to 60 nm tuning range in the 1500 nm communication bands. Prototype filters have been operated in our laboratory for more than 75 million cycles.

## 3. Switchable add/drop filter

Whereas single cavity silicon-based thermo-optic filters as described above are tunable in wavelength, the technology can be extended to multi-cavity hybrids of non-tunable dielectric films combined with tunable semiconductor films. Hybrids of this type display modes of operation quite different from simple wavelength tunability. The add/drop filter reported here is fixed in wavelength but transitions continuously between transmission and reflection by means of temperature change. This is achieved by a multiple cavity thin film

structure combining four conventional cavities made of essentially non-tunable dielectric materials with a single tunable thermo-optic cavity in an integrated coating design.

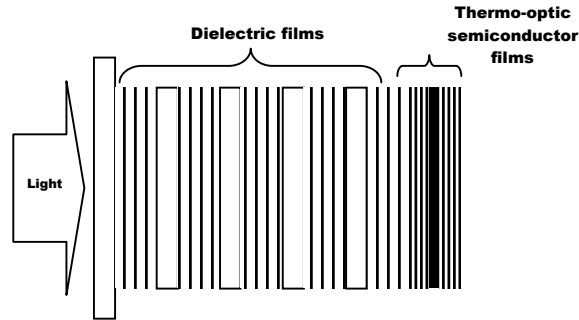


Figure 1. Switchable thin film filter based on combination of dielectric films and thermo-optic semiconductor films.

The principle of operation may be understood from Figure 1 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 by a conventional WDM-qualified filter process such as ion assisted e-beam evaporation or sputtering, using conventional dielectric thin film high/low index combinations such as tantalum pentoxide ( $\text{Ta}_2\text{O}_5$ ) and silicon dioxide ( $\text{SiO}_2$ ) which display very small thermo-optic coefficients, typically resulting in filters with  $0.001 \text{ nm}/^\circ\text{C}$  thermal tunability. On top of this structure, a final, fifth, thermally sensitive, cavity is deposited by PECVD, consisting of a-Si:H / silicon nitride quarter wave mirror pairs and a-Si:H spacer.

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. At this temperature the whole structure behaves as a narrow band transmission filter. As the temperature is further increased above the match point, the five cavity filter again becomes less transmissive and more reflective at the defined channel.

#### 4. Experimental results

Following well known principles of WDM filter design, a four cavity structure was deposited on a white crown glass substrate by ion-assisted e-beam evaporation using three dielectric materials, two of which were  $\text{Ta}_2\text{O}_5$  and  $\text{SiO}_2$ . This portion of the filter has 104 layers and a center wavelength  $1548.3 \text{ nm}$  at  $25^\circ\text{C}$  and, considered by itself, a thermo-optic tuning coefficient  $0.001 \text{ nm}/^\circ\text{C}$ . A fifth cavity was then deposited by PECVD using thermo-optic a-Si:H and non-stoichiometric silicon nitride for an additional 13 layers, with a thermal tuning coefficient  $0.10 \text{ nm}/^\circ\text{C}$ . To match the general properties of the dielectric cavities, only three quarter-wave pairs of the silicon based materials were required for each mirror segment of the semiconductor cavity. The silicon cavity was targeted with a center wavelength of  $1545.8 \text{ nm}$ , so that a temperature increase of approximately  $25\text{-}30^\circ\text{C}$  would bring it into resonance with the existing cavities. As expected, at room temperature  $25^\circ\text{C}$  the resulting mismatched filter stack had very little transmission at any wavelength in the C band.

The results of measuring transmission and reflection spectra at higher temperatures are shown in Figures 2A, B and C. In all curves, the darker trace is transmission and the lighter trace is reflection. Fig. 2A, at the 'resonant temperature'  $49^\circ\text{C}$  indicated by maximum transmission, shows that the bandpass shape was comparable to a conventional  $200 \text{ GHz}$  WDM add/drop filter, with width of  $0.9 \text{ nm}$  at the  $-0.5 \text{ dB}$  points, width of  $2.5 \text{ nm}$  at the  $-25 \text{ dB}$  points, transmission insertion loss of  $-0.95 \text{ dB}$  and reflectivity  $-13.9 \text{ dB}$ . Fig. 2B shows that at a temperature of  $69^\circ\text{C}$  the filter is approximately a 50-50 beamsplitter at the defined channel. Figure 2C, at a temperature of  $164^\circ\text{C}$ , shows that the transmission has been suppressed by  $-18.4 \text{ dB}$  relative to the maximum transmission state at  $49^\circ\text{C}$  and the reflectivity insertion loss becomes  $<-0.5 \text{ dB}$ . (The spurious peak in the suppressed transmission spectrum is accounted for by a thickness error in the topmost quarter-wave of silicon.) The transmissivity and reflectivity at  $1548.3 \text{ nm}$  as a continuous function of temperature are shown in Fig. 3. The excess loss due to absorption in the semiconductor cavity varies from  $<1\%$  at  $164^\circ\text{C}$  to  $14\%$  at the  $49^\circ\text{C}$  resonance.

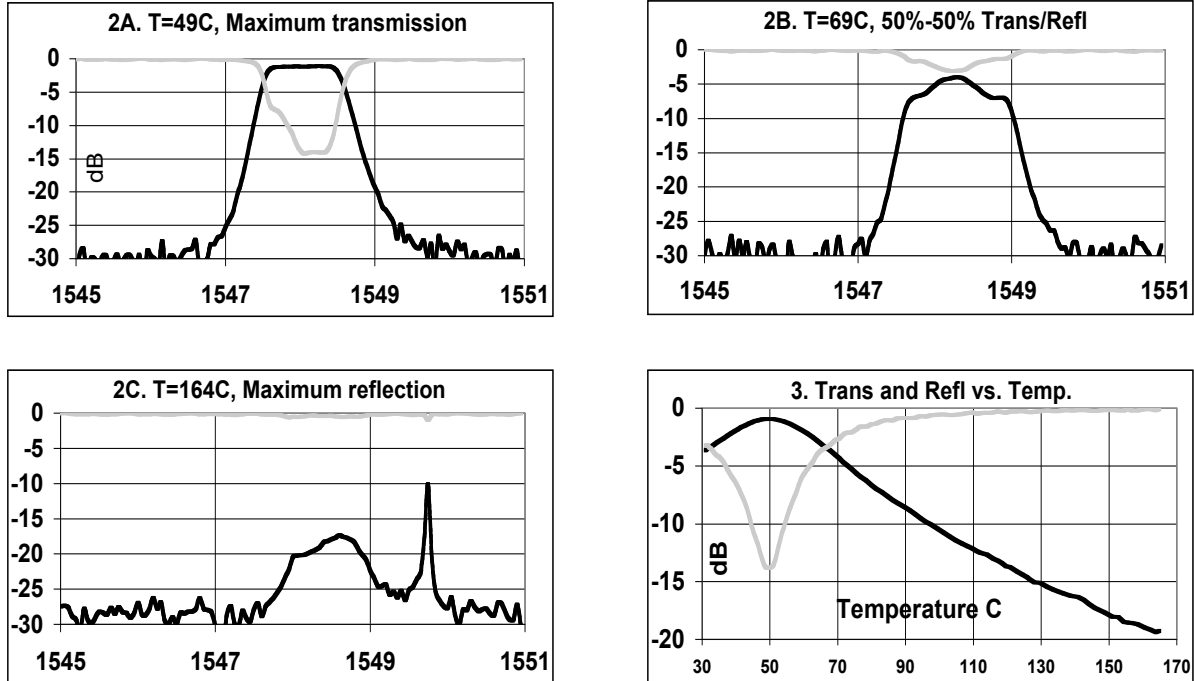


Fig. 2A, B, C. Transmission and reflection at 49°C, 69°C, 164°C.  
 Fig. 3. Transmission and reflection vs. temp. at 1548.3 nm.

## 5. Discussion

We have demonstrated experimentally the principle of a dynamic filter made of dielectric films and cavities combined with semiconductor, thermo-optically active films and cavities. At the resonant temperature the experimental filter is comparable to a standard passive 200GHz narrowband filter. When heated to 164°C, the filter switches to 98% reflective at the channel of operation. A change in ratio of transmission/reflection of 18.4 dB at wavelength 1548.3 nm is seen over the temperature range 49 - 164°C. This property could be used to switch the channel from the drop port to the through port by heating the filter. The 50-50 state observed at 69°C could be useful in a 'drop and continue' network architecture. Continuous variability can replace the function of a variable attenuator. Thus the switchable thin film coating replaces the function of two conventional filters, a 2X2 mechanical switch, and a VOA. In the design exemplified here, the majority of dielectric cavities define the center wavelength, and the single tunable cavity acts either to support or 'spoil' the interference required for narrowband transmission at a fixed wavelength. Many other design variations are possible. By adjusting the mirror reflectivities and spacer thicknesses, the temperature range over which switching takes place may be adjusted from 10-100°C. More generally, by combining a multiplicity of thermo-optic cavities with a multiplicity of passive cavities, it is possible to design structures which produce tunability in both wavelength and transmission/reflection ratio simultaneously, or to tune dispersion, or for dynamic gain flattening. The filters described here may be heated with internal transparent conducting heater films incorporated into the stack or other compact temperature controllers, and packaged similarly to conventional thin film filters within a very small footprint such as a TO can [3]. Based on wafer scale manufacturing and testing, thermo-optic thin films may offer active tunable devices for a variety of network applications at a cost comparable to conventional passive devices.

## 7. References

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