Tunable and Switchable Multiple-Cavity Thin Film Filters

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***Abstract*—A family of thin film interference filters is described that incorporates amorphous silicon layers for wide thermo-optic tunability and the potential for multiple cavity designs. Plasma enhanced chemical vapor deposition (PECVD) of hydrogenated amorphous silicon (a-Si:H) onto fused silica or crystalline silicon wafer substrates produces films with high index ($n = 3.71$), low loss at 1500 nm ($k < 4 \times 10^{-6}$), and thermo-optic index coefficients approximately ten times larger than those of the dielectric materials typically used in wavelength division multiplexing (WDM) filters. Pairing amorphous silicon with low index ($n = 1.77, k = 1 \times 10^{-6}$) silicon nitride companion layers followed by post-process annealing leads to multilayer film stacks which may be cycled up to 400 C without delamination or failure, resulting in thermal index modulations as large as 4% and enabling a wide variety of dynamic thin film device designs. In this paper we survey the range of device applications and show experimental demonstrations for two quite different classes of functionality. One class of filters is tunable in wavelength in the conventional sense. Single and dual-cavity narrowband filters are described with temperature coefficients of center wavelength 85–172 pm/°C in the 1550 nm WDM band and tuning ranges as large as 60 nm, an order of magnitude larger thermal tunability than for conventional thin film narrowband filters. A second class of filters is fixed in wavelength but switchable in transmission, based on hybrid structures which combine tunable semiconductor films and cavities with static dielectric films and cavities in an integrated coating design. To demonstrate the principle of a switchable add/drop filter, we fabricated a five-cavity, 117 layer, 200 GHz filter by combining a single cavity of a-Si:H/a-Si_xN_y films deposited by PECVD with four cavities of dielectrics Ta_2O_5/SiO_2 deposited by ion assisted e-beam evaporation. By varying the temperature, this device can be switched thermo-optically between transmission and reflection states at a fixed channel 1548.3 nm with a contrast ratio 18.4 dB. Stable devices can be obtained even with large internal temperature changes in microscopic volumes provided that layer-to-layer and layer-to-substrate adhesion is robust, film stresses are well controlled through coefficients of thermal expansion matching, and devices are annealed at or above maximum operational temperatures. "Hitless" filters can be obtained by structuring thermo-optic filters in two independently heated portions. Thermo-optically actuated thin film semiconductor devices are manufacturable and testable on a wafer scale and may be packaged by methods adapted from those for conventional thin film filters.**

***Index Terms*—Add-drop filters, multiple cavities, switchable filters, thermo-optic tuning, thin film filters, tunable filters, wavelength division multiplexing (WDM).**

I. Tunable Thin Films and Multicavity Structures

REQUIREMENTS for dynamic fiber optic components, including not only tunable filters but also diverse wavelength management and control devices such as switchable add/drop filters and tunable dispersion compensators, are increasingly important in emerging wavelength division multiplexing (WDM) network architectures. Functionality requirements vary widely by application. For example, filters for monitoring purposes are typically continuously tunable, narrow Fabry-Perots working on a tapped signal so that insertion loss is not critical. On the other hand, tunable add/drop filters in the signal path must provide very low insertion loss, square band pass shapes, large reflection isolation, and controlled chromatic dispersion. In some architectures it is also desireable that they be "hitless," that is, displaying no transmission between target channels. Some of the needs for add/drop filters are "set and forget" applications aimed at reducing filter parts inventories, while others demand rapid tunability for dynamically reconfigurable networks. Still different figures of merit apply to switches and other applications.

A wide variety of tunable or switchable technologies have been developed to meet various of these needs, most prominently based on micro-electro-mechanical systems (MEMS), but also including stretched fiber Bragg gratings, thermo-optic waveguides, liquid crystal devices, and others. Within these diverse approaches it is notable that thin film interference filters, the most widely deployed type of static, fixed WDM filter, have led to relatively few dynamically tunable or switchable counterparts. It is known that thin film narrowband filters may be tuned by mechanical rotation of the angle of incidence [1], and linear variable filters are also commercially available based on spatially graded deposition, tunable by linear translation [2]. However, mechanically actuated filters sacrifice the advantages of thin film compactness and integrability. Recent evaluations of the possibilities for tunable thin films without moving parts, based on strain or electro-optic or piezo-electric effects, have identified few mechanisms that combine wide tunability, acceptable insertion loss and low voltage operation [3], [4]. A practical technology for widely tunable thin film interference coatings would be particularly desireable compared to MEMS approaches if it offered the potential for tunable versions of the multicavity designs and shaped passbands so highly developed in recent WDM filter applications [5].

The family of tunable thin film components described here is based on the incorporation of semiconductor films, in particular 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 compo-

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nents with maximum temperature variability [6]. Moreover, we show that thin film interference coatings incorporating semiconductors can yield practical multiple cavity film stack designs, with the result that "flat top" passband shapes, and a variety of other functionalities not possible in MEMS single-cavity structures, may be achieved. The purpose of this article is to broadly survey the scope of a new technology and show that not only tunable but also switchable devices are possible with diverse applications. To illustrate the range of possible designs, we describe experimental demonstrations of two different classes of thermally activated behavior. The first class comprises filters in which all cavities are made of thermo-optic, semiconductor materials. Such filters are tunable in wavelength in the conventional sense and differ from MEMS tunable filters in offering shaped passbands, compact device form factors, and wafer scale fabrication. We report single cavity filters suitable for monitoring applications and dual cavity filters whose stable bandshape over a wide thermal range demonstrates the feasibility of multicavity designs. The second main class of devices described here are hybrid structures which combine strongly thermo-optically tunable semiconductor films with multiple cavities of essentially static, nontunable dielectric materials, to make filters that are fixed in wavelength but may be thermally switched between transmissive and reflective states [7]. The latter concept may also be extended to "hitless" designs by providing separate heater controls for two parts of a thermo-optic filter stack.

II. Amorphous Silicon for Tunable Interference Coatings

Amorphous semiconductors, developed over many years primarily by the flat-panel display and solar cell industries to take advantage of their electronic properties and suitability for large area, low temperature deposition, are relatively unfamiliar in the photonics and fiber optic device communities. Plasma enhanced chemical vapor deposition (PECVD) is the preferred process for dense, compliant, homogeneous optical coatings of thin film silicon [8]. RF plasma assist permits energetic deposition at low substrate temperatures and offers a highly repeatable process with good lateral uniformity. Control of the basic deposition parameters of PECVD including RF power, total gas pressure, hydrogen partial pressure, gas ratios, flow rates, and substrate temperature can be used to modify packing density and stoichiometry which in turn influence index, optical absorptance, film stresses, layer-to-layer and layer-to-substrate adhesion, and thermo-optic properties. Hydrogenation of the Si films decreases defect densities by quenching dangling bonds, reducing infrared absorptance [9]. Martinu and Poitras reviewed the benefits of PECVD for the physical properties of dielectric optical thin films also, including a wider range of obtainable film stresses compared to physical vapor deposition methods [10]. Film stress engineering is critical for producing thin film devices that can be repeatedly cycled over hundreds of degrees of local temperature change in microscopic volumes without failure by delamination, cracking or bubbling.

Films of hydrogenated amorphous Si (a-Si:H) deposited by PECVD also display large thermo-optic coefficients, ranging from $dn/dT = 2.3 \times 10^{-4}/\mathrm{K}$ at 300 K to $2.9 \times 10^{-4}/\mathrm{K}$ at 480 K as measured by Della Corte and others [10]–[12]. These values are approximately five to ten times larger than those for dielectric materials such as $\mathrm{Ta_2O_5}$ and $\mathrm{SiO_2}$ conventionally used in WDM filters. Using a prism-coupled waveguide propagation technique, we have measured the absorptance of 280 nm thick films of a-Si:H on fused silica to have extinction coefficient $k < 4 \times 10^{-6}$ at 1500 nm, comparable to low loss dielectric materials commonly used in conventional thin film WDM filters. The combination of low absorptance, and large thermo-optic effects make amorphous silicon uniquely suited for thermally tunable thin films in the wavelength range 1.3 to 5 $\mu\mathrm{m}$. 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 $\mathrm{Si_3N_4}$ to nonstoichiometric to alter not only the index but also the film stress over a wide range of tensile and even compressive values [14], a flexibility not available with low index oxides. A possible concern with PECVD silicon nitride is the presence of absorption due to resonance of the N-H bond at 3350 $\mathrm{cm^{-1}}$, whose second harmonic falls at 1510 nm with a width of 60 nm, increasing k of the nitride in part of the telecommunications C band [15].

III. Single Cavity Tunable Filters and Temperature Coefficient of Center Wavelength

Amorphous silicon and silicon nitride films were prepared in a multichamber capacitively-coupled RF powered PECVD reactor using silane and ammonia gases. Deposition temperature setpoint wa 280°C, pressure was 500 mTorr, and the RF power was 3 W for a-Si:H and 8 W for a-$\mathrm{Si_xN_y}$. Deposition rates were approximately 0.5 nm/s. Ammonia/silane ratios were increased in silicon nitride formation in order to obtain nonstoichiometric, low index material. Spectroscopic ellipsometry was used to measure the index profile of a sample single layer film of nitride 915 nm thick, with the result that the index at 1500 nm wavelength was found to be graded through the film thickness, from $n = 1.705$ near the substrate to 1.81 at the top, with a weighted average of 1.77. The nitride thermo-optic index coefficient was about 1/5 that of silicon. Since the deposition temperature was below anticipated operational cycling temperatures up to 350–400°C, an annealing recipe was developed to stabilize devices. The overall upper limit of processing temperature was set by the threshold for silicon microcrystallization at approximately 550°C.

Fig. 1 shows a scanning electron micrograph of a sectioned film stack of a single cavity Fabry-Perot filter deposited by PECVD on a fused silica substrate (S) with the formula $S|(HL)^5 4H(LH)^5|$ air, where $H =$ quarter wave a-Si:H, and $L =$ quarter wave a-$\mathrm{Si_xN_y}$. By virtue of the large index contrast 3.71/1.77, this high/low index pair yields very high mirror reflectivities using only 4–6 quarter wave pairs, compared to 8–10 pairs typically required for $\mathrm{Ta_2O_5/SiO_2}$. Fig. 2 shows a optical micrograph of a device designed for monitoring WDM networks. The central area 400 × 400 $\mu\mathrm{m}$ is the filter, deposited over a polysilicon heater film on a fused silica substrate; the metal areas form the heater circuit. Optical characterization of the deposited layers included secondary ion mass spectrometry (SIMS); Fig. 3 shows that the hydrogren content of a filter with

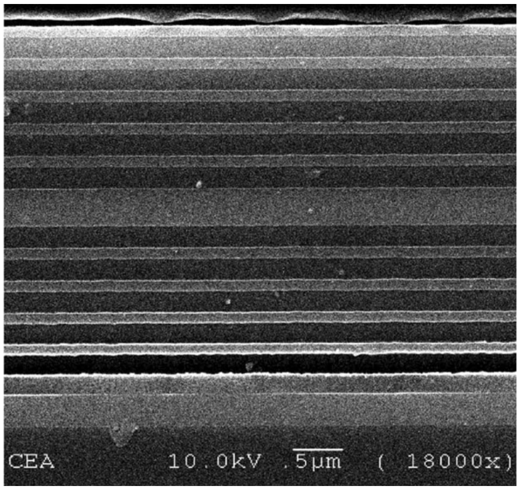

Fig. 1. Scanning electron microscope image of a sectioned filter on a fused silica substrate. Dark regions are silicon nitride, lighter regions are amorphous silicon. Scale bar is 0.5 $\mu\mathrm{m}$.

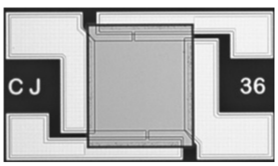

Fig. 2. Microscope image of a single cavity tunable filter, area 1.7 × 0.5 mm; the middle square is the 400 × 400 $\mu\mathrm{m}$ filter, deposited over a polysilicon heater film, provided with four metal contacts for power and for resistance tracking.

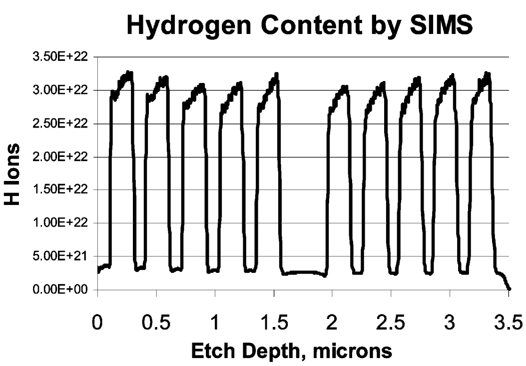

Fig. 3. Hydrogen content of single cavity filter was measured by SIMS (secondary ion mass spectrometry).

four-pair mirrors was graded through each layer, which impacts the distribution of absorptance.

Fig. 4 shows the optical transmission through a 62.5 $\mu\mathrm{m}$ diameter collimator spot for a filter on a silicon wafer substrate with the formula

$$\mathrm{Susbstrate}\ |L(HL)^5 4H(LH)^6|\ \mathrm{air}$$

at two oven temperatures, 25$^\circ\mathrm{C}$ and 125$^\circ\mathrm{C}$. Based on the bulk optical constants of the two materials, the theoretical insertion loss and full width half maximum (FWHM) would be -1.1 dB and 35 pm, respectively, (finesse $\approx$ 22 000), but such a narrow Fabry-Perot is unlikely to be realized in practice. The measured insertion loss was -4.1 to -4.8 dB and the FWHM was 190 pm at the lower temperature for a finesse $\approx$ 4,000. The discrepancy between theoretical and measured values is accounted for by

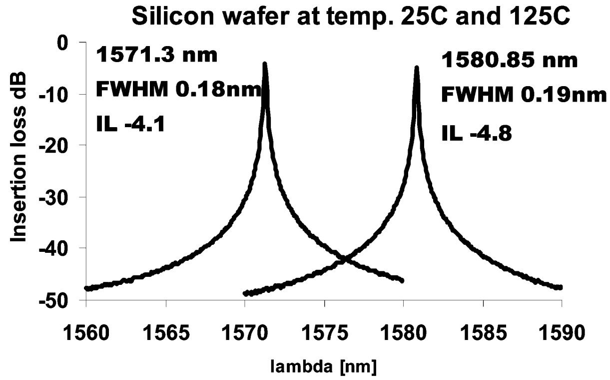

Fig. 4. Filter on silicon wafer substrate.

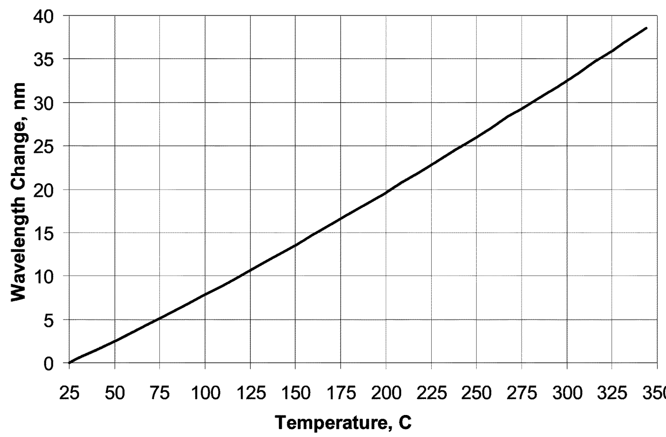

Fig. 5. Change of center wavelength versus temperature for a single cavity filter.

a combination of small effects including increased absorptance in the outer silicon layers due to hydrogen loss, scattering in the interfaces, depositional nonuniformity of spacer thickness on the order of 0.5% over 20 mm of wafer area, and temperature nonnuniformity $<1^\circ\mathrm{C}$ within the collimator spot.

In Fig. 4 the coefficient of thermal tuning of center wavelength over the 25–125$^\circ\mathrm{C}$ temperature range is $d\lambda/dT = 96\ \mathrm{pm}/^\circ\mathrm{C}$. Thermo-optic tunability $d\lambda/dT$ can be maximized in two ways. As may be shown by standard thin film theory, the presence of thermo-optic layers not only in the spacer layer but also in the mirror layers of a Fabry-Perot thin film filter increases the effective tunability by approximately 10%, due to the increased phase dispersion of the mirrors [5], and for similar reasons tunability is raised an additional 10% by increasing spacer thickness from 2QW to 6QW.

Fig. 5 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$^\circ\mathrm{C}$ for a mean rate of 123 pm/$^\circ\mathrm{C}$. Fig. 6 shows consolidated measurements of thermal coefficients of wavelength tunability $d\lambda/dT$ as a function of temperature collected for a number of single cavity samples (all with six-period mirrors and 4QW spacers on fused silica substrates) under various conditions including oven heating of unpackaged chips, internal film heating of packaged devices, and as processed by means of various annealing recipes. Coefficients $d\lambda/dT$ range from 85 pm/$^\circ\mathrm{C}$ near room

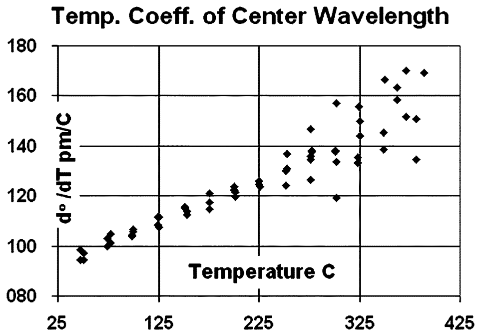

Fig. 6. Filter temperature coefficient of center wavelength $d\mu/dT$ in pm/$^\circ$C versus temperature; consolidated data from devices with various packaging and annealing conditions.

temperature to 172 pm/$^\circ$C at 400°C, consistent with the dn/dT behavior of bulk amorphous silicon, whose excitonic band edge is strongly temperature dependent [12].

For comparison, Takashashi, in his study of filter-substrate interactions, measured thermal coefficients of wavelength tuning for typical conventional dielectric filters on fused silica substrates on the order of 14 pm/$^\circ$C [16]. Takashashi's elasto-optical model, developed in an effort to manage and minimize thermal tunability of wavelength of narrow-band WDM filters, indicates that use of substrates with larger coefficients of thermal expansion (CTE) would be expected to reduce the net thermal tunability because the larger CTE substrate tends to shrink the filter thickness in proportion to the filter Poisson ratio as the temperature increases, offsetting the positive thermo-optic effect. In our case however, the strong thermo-optic properties overwhelm the substrate CTE effects and the change from fused silica substrate $(\mathrm{CTE} = 1 \times 10^{-7}/\mathrm{K})$ to crystalline silicon $(\mathrm{CTE} = 25 \times 10^{-7}/\mathrm{K})$ substrates did not significantly impact $d\lambda/dT$. Thus, for thermo-optic semiconductor based filters, the type and preparation of substrate can be chosen to manage the match of CTEs throughout the structure and thereby minimize film stresses.

Even with the large values of $d\lambda/dT$ we recorded, tuning over the full 32 nm C band 1530–1562 nm requires cycling a microscopic volume of filter over a wide temperature range approximately 25–270°C. Heating is accomplished in packaged chips either by means of an internal heater film of electrically conductive doped polysilicon integrated into the optical film stack, or else by a doped conductive region on a crystalline silicon substrate.

IV. Stability for Telecommunications Applications

Any dynamic device technology proposed for telecommunications applications must meet demands for acceptable power consumption and response time, and stringent reliability and service life exceeding 20 years. An indication of basic stability of thermo-optic thin films described here may be found in the performance of a single cavity filter in an optical monitor application (tunable detector). Fig. 7 shows schematically the basic geometry of a filter deposited over a patterned polysilicon heater, and Fig. 8 shows the design of a packaging configuration for the tunable detector with the filter, heater film, detector and a pigtailed collimator all integrated into a TO can. Using internal heating layers, experimental chips have been tuned over ranges exceeding 60 nm without failure, but long term reliability is improved with smaller tuning ranges. Fig. 9 shows results of life testing of the optical stability of packaged single cavity filters incorporated in optical channel monitors scanning a 29 nm tuning range ten times each second, with an internal temperature excursion within the filter layers approximately $\Delta T = 235^\circ\mathrm{C}$ in each cycle and an average power consumption of 150 mW. This data, consolidated from eight test units, shows that the repeatability of center wavelength at a given film temperature, recorded over sixteen million scans (450 continuous hours), is less than 0.02% (or 39 GHz). In contrast with MEMS, thin film devices can be tested at the wafer scale. Fig. 10 shows a four inch fused silica wafer containing several thousand devices.

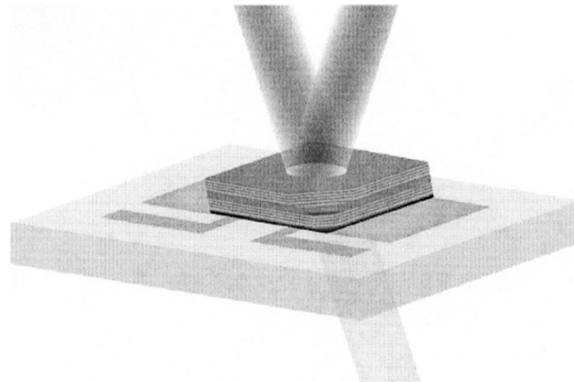

Fig. 7. Schematic showing single cavity filter deposited over heater film (doped polysilicon) integrated into the optical stack, electrical pads and fused silica substrate.

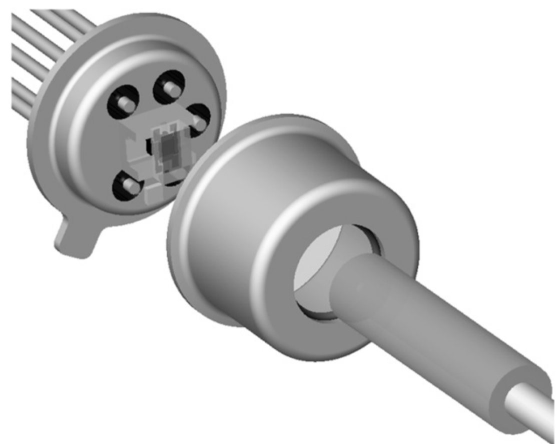

Fig. 8. Design for packaged optical channel monitor or tunable detector, showing the filter chip incorporating heater film, chip carrier, header, TO can and fiber pigtail. Detector sits below the chip.

V. Dual Cavity Tunable Filters

Single cavity Fabry-Perot filters are characterized by sharply peaked passbands and broad skirts. Thus they are useful for optical monitoring purposes, but less so for in-path network applications such as add/drop filters, where a square passband is normally required. Also, as discussed earlier, square filters are

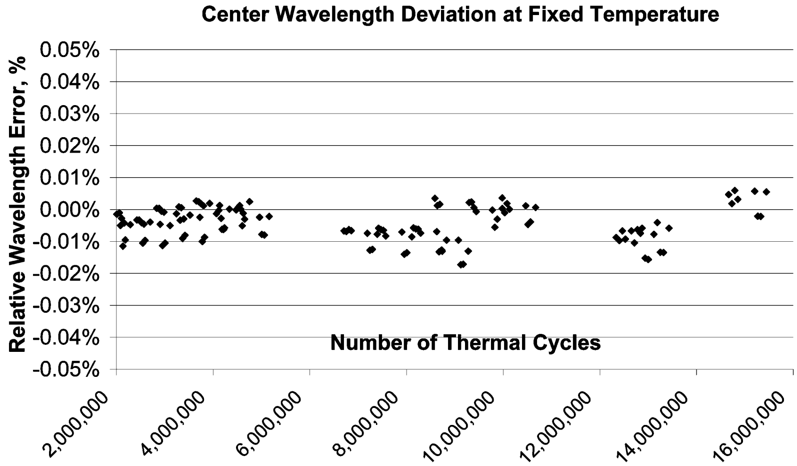

Fig. 9. Life test data consolidated for eight test devices, showing the stability of wavelength at a given temperature over 16 million scans, ten scans per second, total 444 hours.

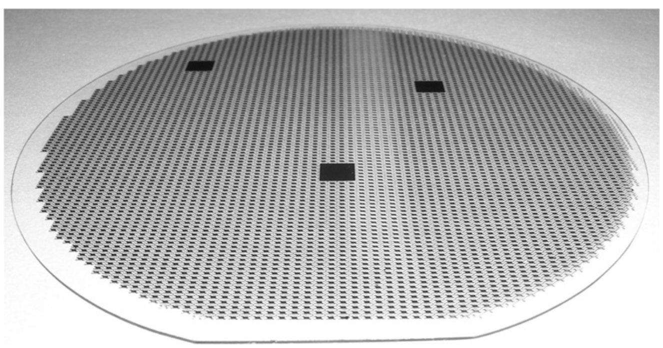

Fig. 10. Four inch fused silica wafer containing several thousand tunable filters with supporting heater circuits. The larger patches are test filters.

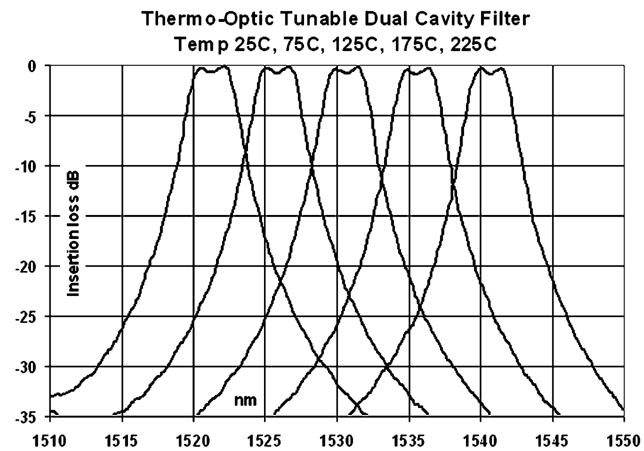

Fig. 11. Dual cavity filter transmission at temperatures 25–225 μC.

less vulnerable than the narrow peaks of high-finesse filters to broadening and increased insertion loss due to a variety of small perturbations such as interlayer scattering, finite spot size, and lateral nonuniformity of deposition or heating.

Deposition of dual cavity filters differs from single cavities in that much more precise calibration of optical thicknesses is required, particularly to match the several spacer layers to 0.01%. Initial experiments using three-pair mirror stacks were primarily directed at answering the question whether the cavity-layer matching achieved during deposition would be maintained over the large temperature ranges required for tunability of 30 nm or more. Fig. 11 shows the transmission through a dual cavity filter on fused silica with the formula

$$S|(HL)^3 4H(LH)^3 L(HL)^3 4H(LH)^3| \text{ air}.$$

At 25°C the insertion loss over the central 1.6 nm passband varies from -0.05 to $-$ 0.67 dB. The thermal tuning coefficient over the range 25–225°C is 95 pm/°C, similar to the single cavity case. Note the slight narrowing of the filter shape as the temperature is increased. This is explained by the much larger dn/dT for a-Si:H than for a-$\mathrm{Si}_x\mathrm{N}_y$, which causes the index contrast between H and L layers to increase from 3.71/1.77 at room temperature to 3.725/1.773 at 225°C, with the effect of increasing the mirror reflectivities, narrowing the spectral width, and slightly increasing the insertion loss. Other than this expected effect however, Fig. 11 demonstrates that the 21 layer dual cavity filter maintains its bandshape over this temperature range, indicating a high degree of thermal uniformity and verifying that the matching of the two spacer layer optical thicknesses to better than one part in 10^4 achieved during deposition is preserved as the filter is thermally tuned. Finally, the insertion loss of the dual cavity filter is close to its theoretical value, indicating that as expected it is less susceptible to small nonuniformities than in the case of very narrow single cavity filters. While design studies using our materials show that filters with three or more cavities and 56 or more layers are necessary to meet commercial add/drop filter requirements, the 21 layer dual cavity data here suggests this is feasible if enabled by accurate monitoring of the deposition process and controlled film stresses.

VI. Hybrid Semiconductor—Dielectric Filters

Having discussed single and dual cavity thermo-optic tunable filters, we will now describe experimental demonstration of a second class of multicavity devices which are fixed in wavelength but switchable in transmission.

The motivation for such a device is the development of a low cost, compact switchable add/drop filter. Current commercially available switchable add/drop filters typically are modules

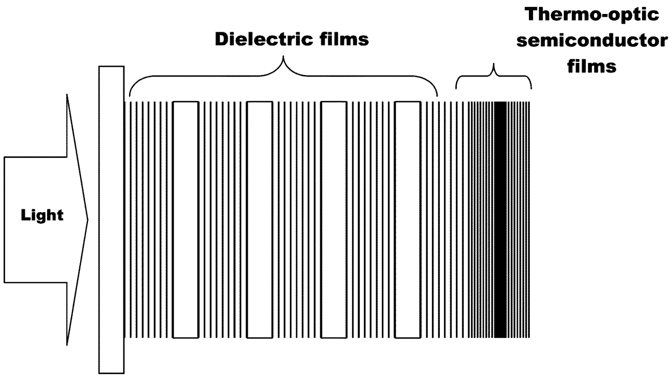

Fig. 12. Schematic of a switchable add/drop filter based on combination of four nontunable dielectric cavities with a single thermo-optically tunable semiconductor cavity. The five cavities are initially mis-matched at room temperature, and the filter is transmissive only at a higher "resonant temperature."

which for each channel combine separate elements including two thin film filters, a mechanical switch and in some cases a variable optical attenuator.[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, reducing components count.

Based on the principles described above, it is possible to fabricate an extremely compact thin film filter that switches thermo-optically between transmissive and reflective states at a fixed wavelength channel. This can be accomplished by adding a single thermo-optic cavity on top of a "substrate" which is itself a dielectric multicavity filter. The resulting integrated thin film interference coating comprises n cavities, $n-1$ of which are made using conventional dielectric materials and the last using strongly thermo-optic layers of amorphous silicon. By temperature tuning, the n cavities can be brought into or out of resonance, switching between transmission and reflection at the fixed channel.

VII. Switchable Add/Drop Filter

An example of a hybrid multicavity structure of nontunable dielectric films combined with a single tunable semiconductor cavity is described as follows. The principle of operation may be understood from Fig. 12 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 on a high-CTE substrate, which then display very small thermal tunability of center wavelength. On top of this structure, a final, fifth, thermally sensitive, cavity is deposited by PECVD, consisting of a-Si:H/a-Si_xN_y quarter wave mirror pairs and a-Si:H spacer, in an integrated coating design.

The fifth spacer thickness is deposited such that at room temperature its resonant wavelength is a few nanometers below that of the underlying four passive cavities, with the result that filter is almost totally reflective (nontransmissive) at the design channel. As the temperature of the device is increased, a "resonant temperature" is reached where the fifth tunable cavity becomes phase matched to the group of four fixed cavities. At the resonant temperature the whole structure behaves as a single integrated narrow band interference coating. As the temperature is further increased above the resonance point, the five cavity filter again becomes less transmissive and more reflective at the defined channel.

An experimental demonstration of a five cavity 200 GHz filter was constructed as follows. The lower four-cavity portion was a pre-existing design deposited on a white crown glass substrate (chosen to minimize thermal tunability) by ion-assisted e-beam evaporation using Ta_2O_5 and SiO_2 and ending with the latter layer. Standard optical monitoring techniques were used to match the four cavities. 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 about 1 pm/°C. A fifth cavity was then deposited by PECVD using thermo-optic $H =$ a-Si:H and $L =$ silicon nitride for an additional 13 layers, with the formula

$$\text{Dielectric filter } |(HL)^3 2H(LH)^3| \text{ air}$$

with a thermal tuning coefficient, considered by itelf, approximately $d\lambda/dT = 100 \text{ pm}/^\circ\text{C}$. To match the mirror reflectivities as closely as possible to those of the dielectric cavities, only three quarter-wave pairs of the silicon based materials were used for each mirror segment. The silicon spacer 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 pre-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.

The results of measuring transmission and reflection spectra as the temperature was increased are shown in Fig. 13(a)–(d). Fig. 13(a), at the "resonant temperature" 49°C indicated by maximum transmission, shows that the bandpass shape was comparable to a conventional 200 GHz WDM add/drop filter, with width of 0.9 nm at the − 0.5 dB points, width of 2.5 nm at the − 25 dB points, transmission insertion loss of − 0.95 dB, and reflectivity − 13.9 dB. Fig. 13(b) shows that at a temperature of 69°C the filter is approximately a 50–50 beamsplitter at the defined channel. Fig. 13(c), at a temperature of 164°C, shows that the transmission has been suppressed by − 18.4 dB relative to the maximum transmission state at 49°C and the reflectivity insertion loss becomes < -0.5 dB. (The spurious peak in the suppressed transmission spectrum is accounted for by thickness errors in the top quarter-waves of silicon.) The transmissivity and reflectivity at 1548.3 nm as a continuous function of temperature are shown in Fig. 13(d). Fig. 14 shows the excess loss due to absorption in the semiconductor cavity, varying from $<1\%$ at 164°C to 14% at the 49°C resonance. Because in this experiment the dielectric portion of the filter was a pre-existing design and the five cavities were not fully optimized as a single structure, the reflectivity isolation, passband ripple, and chromatic dispersion could be expected to improve in an integrated symmetrical design.

[1]Current reconfigurable add/drop technology is represented by commercial products of JDSU, as described at http://www.jdsu.com/site/images/products/pdf/coadm_apnote.pdf

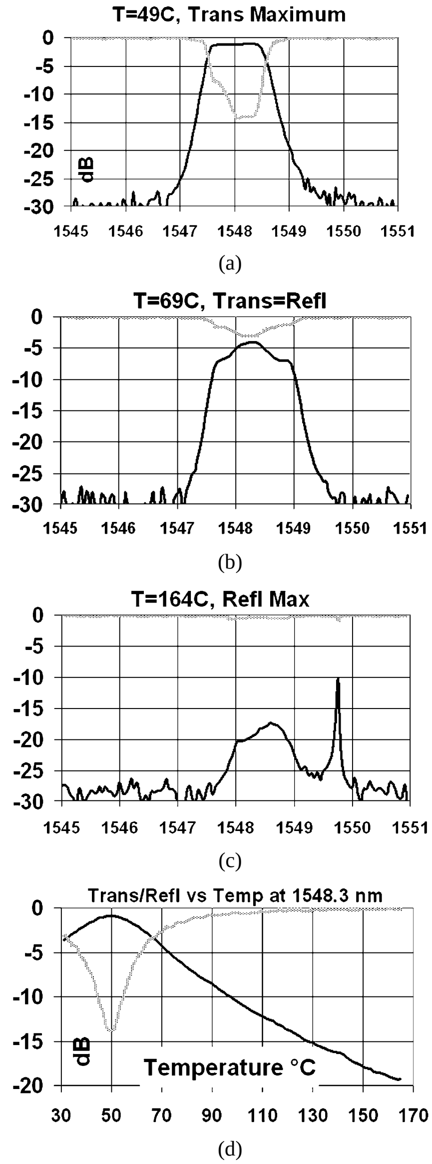

Fig. 13. (a) Transmission (dark curve) and reflection (light curve) spectra at the "resonant temperature" 49°C of maximum transmission. (b) Transmission and reflection are equal (50–50 beamsplitter) at 69°C. (c) At temperature 164°C, transmision is suppressed by 18.4 dB and filter is almost entirely reflective. (d) Transmission and reflection at the fixed wavelength 1548.3 nm as a function of temperature.

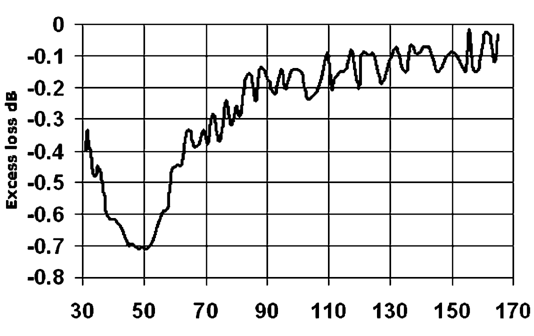

Fig. 14. Excess loss versus temperature.

Variants on this design are possible. By adjusting the mirror reflectivities and spacer thicknesses, the temperature range over which switching takes place may be adjusted between 10–100°C. These properties could be used to switch the channel from the drop port to the through port by heating the filter. Continuous variability can replace the function of a variable attenuator. Thus in a reconfigurable add/drop module, shown in a conventional version in Fig. 15, a single compact switchable thin film coating could replace the function of conventional filters, a 2×2 mechanical switch, and a variable optical attenuator, as indicated in Fig. 16.

VIII. "HITLESS" TUNABLE FILTERS

The concept of Section VII may be extended to an approximately "hitless" tunable filter which is transmissive at targeted channel wavelengths but substantially less so during the tuning process. Fig. 17 shows a design concept in which the hybrid thermo-optic/passive dielectric structure is replaced by an all-thermo-optic design which is divided into two portions separated by a precisely fabricated thermally insulating gap (an even number of half waves of air or fused silica) and provided with two independent heater films. As a coherent structure, a multi-cavity filter (including the precisely defined "absentee" gap) is designed as a 100 GHz add/drop filter. For hitless operation, the filter is tuned from one channel to another in a two-step sequence of operations. Initially, the temperature of the upper portion, T_u matches that of the lower portion, $T_u = T_l$, so that the whole acts as a single coherent design. In the first step of tuning to a new channel, the temperature of the upper portion is changed from that of the lower by means of the upper heater film, $T_u' > T_l$, causing the transmission to be suppressed. In the second step, the temperature of the lower portion is also changed, to realign it with that of the top, $T_l' = T_u'$, the two portions now being in synchrony again but at a new channel. The insulating film gap may be air, or alternatively fused silica, whose thermal conductivity is small and whose thermo-optic index coefficient is $dn/dT = 9.9 \times 10^{-6}$K at 300 K, about 1/25 that of amorphous silicon and essentially nontunable [12]. To fabricate such a structure with an air gap, the silicon/silicon nitride structure is desposited on a silicon wafer substrate with the deposition in two parts separated by a silicon dioxide layer which is then patterned by a mask and etch step to provide a partial region of air gap.

As an example of such a design, consider a three cavity 100 GHz filter with 65 layers using only $H =$ quarter wave amorphous silicon and $L =$ quarter wave silicon nitride and the insertion of an extra 20 quarter waves of air at a layer determined to be relatively insensitive to optical thickness variations:

$$0.2814L\ 0.3617H\ 0.2814L\ L(HL)^3$$
$$6H$$
$$L(HL)^4 0.4661L\ 0.0529H\ 0.4661L\ L(HL)^4$$
$$6H$$
$$L(HL)^4 0.4661$$
$$20Air$$
$$L\ 0.0529H\ 0.4661L\ L(HL)^4$$
$$6H$$
$$L(HL)^3 0.2814L\ 0.3617H\ 0.2814L$$

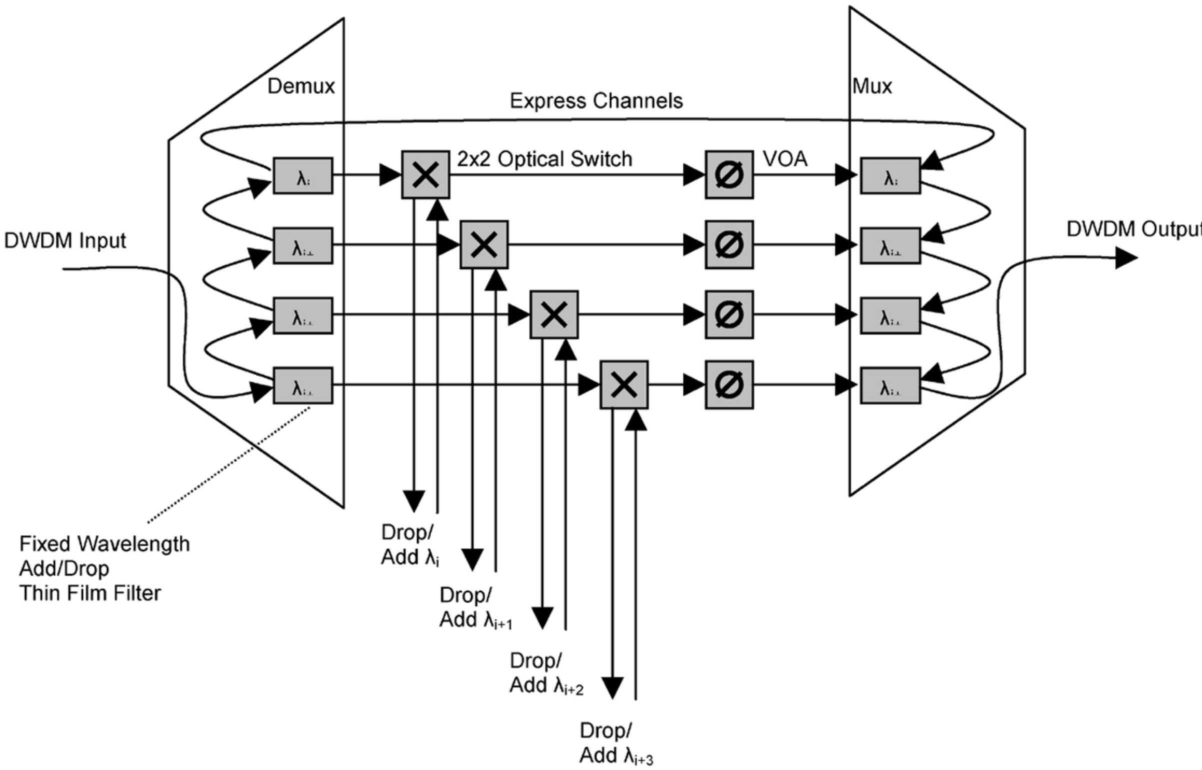

Fig. 15. Conventional reconfigurable add/drop module shown for four channels contains, for each channel, two fixed thin film filters, a 2 $\times$ 2 optical switch, and a variable optical attenuator.

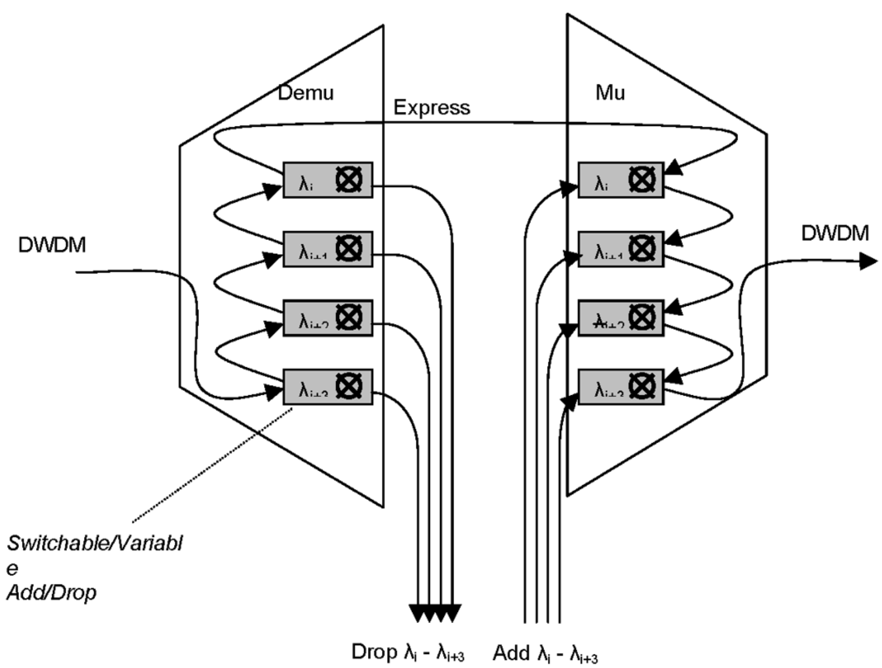

Fig. 16. Use of switchable add/drop filters provides the same functionality as in Fig. 15 but eliminates the optical switches and variable attenuators.

A simulation of the optical transmission is shown in Fig. 18 with the filter designed for center wavelength 1550 nm. At 25°C, this design is configured to have a bandwidth of 55 GHz at $-$ 0.5 dB, bandwidth of 174 GHz at $-$ 25 dB, peak insertion loss of $-$ 0.3 dB and $>$ 23 dB reflection isolation. The different curves in Fig. 18 indicate the decay of the transmission spectrum as the lower portion is heated divergently from the upper by 90°C. As the two portions are then matched again at the higher temperature, the transmission is reconstituted at 1557.7 nm. The transmission is substantially suppressed at

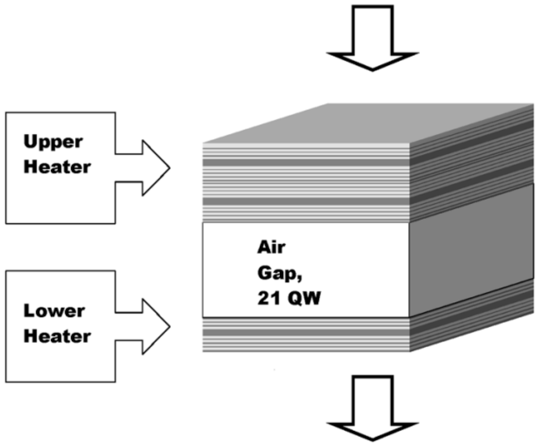

Fig. 17. Schematic of a "hitless" tunable filter. A three cavity, 65 layer thermo-optic 100 GHz filter is divided with a 20 quarter wave air gap and separate heater films are provided for the upper and lower parts.

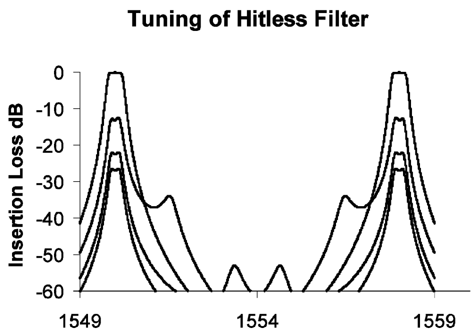

Fig. 18. Tuning behavior in two steps. Read down on the left side; parts are divergently heated, transmission decays. Read up on the right side; two parts are matched again at a 90 C higher temperature, the bandshape is reconstituted at 1557.7 nm.

wavelengths inbetween during the tuning process. A possible limitation in this design is that the air gap, being nontunable, contributes an increasing phase error as further channels are tuned, but this can be minimized by choosing a relatively insensitive layer in which to insert it.

IX. Summary and Conclusion

We have demonstrated experimentally a new family of dynamic thin films and tunable multicavity filters based on thermo-optic effects in amorphous silicon. Combination of large thermo-optic coefficients with large temperature changes in microscopic volumes offers index modulations as large at 4%, a scale of index control which is difficult to obtain through any other thin film approach. Tunable single cavity filters show thermal coefficients of central wavelength tuning of 85–172 pm/°C, approximately ten times larger than for conventional dielectric filters on fused silica. Single cavity devices are able to reliably scan 40 nm or more by use of internal heater layers. A dual cavity tunable filter was demonstrated which maintains the integrity of its spectral shape over a temperature range of 200°C. A hybrid filter was demonstrated, made of dielectric films and cavities combined with a single cavity of semiconductor, thermo-optically active films, resulting in switchable rather than tunable behavior. At the resonant temperature the experimental filter is comparable to a standard passive 200 GHz narrowband filter. When heated to 164°C, the filter switches to 90% reflectivity 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. A "hitless" tunable filter may be constructed by dividing a multicavity thermo-optic filter into two separately controlled parts. The amorphous silicon approach to tunable or switchable filters allows them to be manufactured more like flat panel displays than conventional photonic devices, and tested on a wafer scale. Active thin film devices may be packaged similarly to conventional thin film filters within a compact form factor such as a TO can, potentially leading to tunable, switchable or dynamic devices for a variety of network applications with a simplicity comparable to conventional passive devices.

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