Substrate-strain-induced tunability of dense wavelength-division multiplexing thin-film filters

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Classic dense wavelength-division multiplexing thin-film filters can be spectrally tuned through the substrate's strain. We analyze the theoretical shift of the design wavelength of a narrow-bandpass filter when uniform, uniaxial compressive stress is applied to the substrate, and we compare calculated sensitivity with experimental data. We measure the transmittance shape of a 200-GHz standard filter for several loading cases to quantify the increase of insertion losses. © 2003 Optical Society of America

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A narrow-bandpass filter (NBPF) is a key component of many wavelength-selective devices used in dense wavelength-division multiplexing (DWDM) fiber-optic networks such as add and drop, multiplexers, and demultiplexers. Among the various technologies implemented to achieve such passive NBPFs, thin-film deposition techniques are competitive in terms of manufacturing costs and achievable optical performance. DWDM was introduced in the early 1990s and was the cause of a dramatic increase in the transmission capacity of telecommunication fiber-optic networks. More recently, we observed a growing demand for active or reconfigurable versions of the passive optical devices listed above.

In a previous paper[1] the present authors and others analyzed from a theoretical point of view the various physical means that one can implement to achieve tunability of DWDM thin-film filters. In particular, we showed how temperature and electric field can be used to induce a change in the optical thickness of one or more layers directly inside the stack or through the substrate. Experimental results on the piezoelectric properties of Ta_2O_5 thin films deposited at high temperature by classic electron-beam evaporation were reported,[2] but there was limited interest in use of such active thin-film layers to produce tunable NBPFs because of their intrinsic low tuning range and high scattering losses.

In this Letter we present a more detailed analysis of the tunability of a NBPF thin-film filter induced by a mechanical strain applied to its substrate. The experimental demonstration of such an effect is emphasized and quantified, for the first time to our knowledge. Our original idea comes from a reflection on Takashashi's paper[3] on temperature stability of thin-film NBPFs. In his paper Takashashi describes how an appropriate choice of the substrate, in terms of the coefficient of linear expansion, allows an increase in the refractive index of the filter layers created by a temperature change to be balanced by a decrease of their thickness induced by a differential thermal expansion between the layers and the substrate. We can infer from this idea that, if the temperature is kept constant, a mechanical deformation of the substrate, i.e., a strain, can be used to induce a shift in the design wavelength of the filter.

However, unlike Takashashi, we prefer to adopt a theoretical description based on a direct tensor calculation, taking into account first the elastic properties of both substrate and filter and second the elasto-optic coefficients of the stack layers. This approach is well adapted to DWDM filters because of the lack of porosity inside the layers, which is ensured by their manufacturing process (either ion-assisted deposition or dual-ion-beam sputtering).

Let us consider the geometry shown in Fig. 1. The NBPF is deposited upon a substrate whose Young modulus and Poisson coefficient are, respectively, Y_s and ν_s. We take a parallelepiped substrate with dimensions (b, a, a) along the three axis directions. Following Takashashi, we assume that the filter can be replaced by a single layer whose mechanical thickness is equal to the thickness of the stack and with a refractive index given by

$$n_{\mathrm{eq}} = n_L/[1 - (n_L/n_H) + (n_L/n_H)^2]^{1/2} \tag{1}$$

for a NBPF cavity with low-index material and by

$$n_{\mathrm{eq}} = \sqrt{n_L n_H} \tag{2}$$

for a NBPF cavity with high-index material. In both cases, n_L and n_H are the refractive indices of the

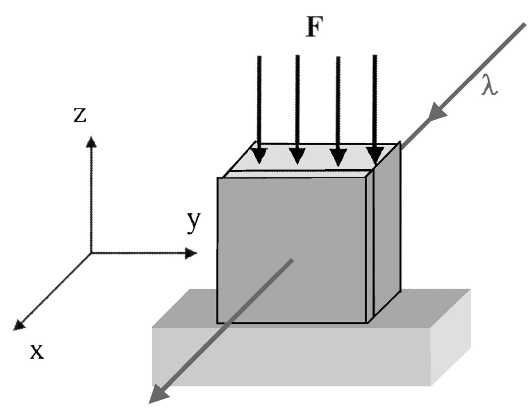

Fig. 1. Geometry used for the tensor calculation of changes in refractive index and mechanical thickness when the filter is loaded with a uniform uniaxial force F.

low- and the high-refractive-index layers, respectively. We designate the Young modulus of this equivalent layer Y_f and its Poisson coefficient ν_f. We also need to define elasto-optic tensor $\mathbf{p}$ of this equivalent layer. If we assume that the filter is a centrosymmetric material, we can write

$$\begin{pmatrix} \Delta(1/{n_1}^2) \\ \Delta(1/{n_2}^2) \\ \Delta(1/{n_3}^2) \end{pmatrix} = \begin{bmatrix} p_{11} & p_{12} & p_{12} \\ p_{12} & p_{11} & p_{12} \\ p_{12} & p_{12} & p_{11} \end{bmatrix} \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{pmatrix}, \qquad (3)$$

where ϵ_i is the strain along direction i and n_i is the refractive-index value in the same i direction. When no stress is applied, we consider an isotropic layer such that $n_i = n_{\mathrm{eq}}$ for all i values.

We assume, for instance, a uniform uniaxial compressive force F applied to the substrate, as shown in Fig. 1. This force causes substrate strain in all directions: a direct compressive strain along the z (or third) axis and an induced strain caused by elasticity of the material for both the x and the y directions. We assume that the adhesion of the film to the substrate is ideal, such that any dimension change of the substrate in its plane is transferred to the film itself. The final result is a change in the film's mechanical thickness t_f as predicted by the elastic-strain relations that describe the film's behavior, i.e.,

$${\epsilon_i}^f = \frac{1+\nu_f}{Y_f}\,{\sigma_i}^f - \frac{\nu_f}{Y_f}\,({\sigma_1}^f + {\sigma_2}^f + {\sigma_3}^f)\,, \qquad i = 1, 2, 3\,, \qquad (4)$$

and a change in its refractive indices n_1, n_2, and n_3 in accordance with the elasto-optic tensor presented above. We are naturally concerned mainly with n_1, because the relative center wavelength shift $\Delta\lambda/\lambda$ is defined by

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta(n_1 t_f)}{n_1 t_f} = {\epsilon_1}^f + \frac{\Delta n_1}{n_1}\cdot \qquad (5)$$

In the particular case defined in Fig. 1, ${\sigma_1}^f = 0$, whereas ${\sigma_2}^f$ and ${\sigma_3}^f$ can be calculated from strain relations. The result is

$$\frac{\Delta\lambda}{\lambda} = \frac{1-\nu_s}{1-\nu_f}\left\{\nu_f + \frac{{n_{\mathrm{eq}}}^2}{2}\,[(1-\nu_f)\,p_{12} - \nu_f\,p_{11}]\right\}\frac{F}{SY_s}\cdot \qquad (6)$$

One can naturally use this kind of approach, based on elastic-strain tensor and elasto-optic tensor relationships, to evaluate the thermal behavior of a standard DWDM filter:

$$\frac{1}{\Delta T}\,\frac{\Delta\lambda}{\lambda} = \frac{1}{n}\,\frac{\mathrm{d}n}{\mathrm{d}T} + \beta - \frac{2(\alpha-\beta)}{1-\nu_f} \times \left\{\nu_f + \frac{{n_{\mathrm{eq}}}^2}{2}\,[(1-\nu_f)\,p_{12} - \nu_f\,p_{11}]\right\}, \qquad (7)$$

where α (β) is the coefficient of thermal expansion of the substrate (equivalent layer) and $(1/n)(\mathrm{d}n/\mathrm{d}T)$ is the thermal sensitivity of the refractive index of this equivalent layer.

In his paper Takashashi showed that the properties of an ion-assisted deposition NBPF equivalent layer can be described with the physical parameters of fused silica. We use the same approach [$\beta = 5.5 \times 10^{-7}/°\mathrm{C}$, $(1/n)(\mathrm{d}n/\mathrm{d}T) = 10^{-5}/°\mathrm{C}$, $\nu_f = 0.17$], which we extend to the elasto-optic coefficients ($p_{11} = 0.121$ and $p_{12} = 0.27$). Moreover, we consider a low-index cavity $SiO_2{-}Ta_2O_5$ filter ($n_{\mathrm{eq}} = 1.64$), with standard dimensions (1.4 mm × 1.4 mm × 0.8 mm) and substrate mechanical properties ($\nu_s = 0.25$, $Y_s = 78$ GPa).

For thermal loading, the conclusions provided by our model are identical to Takashashi's (cancellation of the thermal sensitivity of the filter when the substrate's coefficient of thermal expansion is $\sim 110 \times 10^{-7}/°\mathrm{C}$). For uniform uniaxial compressive stress the calculated sensitivity of the design wavelength of a NBPF with respect to the applied force is close to 7 pm/N (see Fig. 2, dashed line). This means that a tuning range as large as 7 nm can be reached by selection of stress below the compressive breaking point of the substrate (typically 1.1 GPa, which here means ~1000 N).

To confirm our theoretical evaluation we developed a setup that allowed us to make an accurate measurement of the spectral transmittance of a classic DWDM filter stressed by a compressive force measured in real time.

We saw above that, under compressive stress, the central wavelength is shifted toward larger wavelengths. However, it is well known that an angular tilt tends to shift the center wavelength toward shorter wavelengths. As a consequence, a compressive force effect cannot be confused with an angular tilt. Nevertheless, to reach an accurate determination of the filter's strain sensitivity we need to minimize this potential angular contribution. Toward this goal, we used a specially designed filter holder that defines with accuracy the measuring area at the filter surface (because of the presence of a circular hole of 1-mm diameter) and whose internal dimensions are tightly matched to the filter's dimensions (to prevent any kind of filter displacement or tilt during the application of force). Moreover, we verified for each change in the applied force that the angular orientation of the filter remains identical with respect to that of the incident beam (accuracy better than 30 arc sec). Finally, we placed at the bottom of the filter holder a dedicated sensor that provides a direct determination of the force applied to the filter itself: The measuring limit of this sensor is 500 N, half of the theoretical breaking point of an ideal fused-silica substrate.

The filter is inserted between two identical LightPath pigtailed collimators with waists located at the filter surface (waist diameter, ~500 μm), so the working conditions are similar to those found in commercial

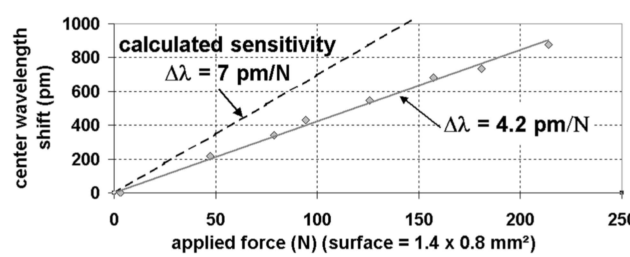

Fig. 2. Center wavelength shift: experimental data, solid line; simulated data, dashed line.

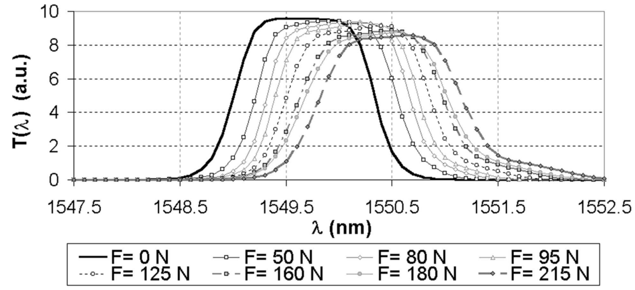

Fig. 3. Experimental transmittance curves for several cases of uniform loading.

systems. To record the spectral transmittance of the filter, we directly connect the fiber pigtail of the input collimator to an Exfo tunable laser (tuning range, 1520–1570 nm; wavelength repeatability, ~10 pm), whereas the output fiber is connected to an InGaAs photodiode followed by a low-noise current amplifier and a 16-bit digital-to-analog converter. The entire setup is computer controlled.

When no stress is applied to the filter, its spectral response is that of a classic 200-GHz thin-film filter centered about International Telecommunication Union channel 35 (1549.32 nm); its full width at half-maximum (FWHM) is ~1.4 nm. When compressive stress is applied to the filter substrate, we observe, as expected, a shift of the central wavelength of the substrate toward larger wavelengths (Fig. 2, solid line, and Fig. 3). The shift value is proportional to the applied force; the slope of this behavior is 4.2 pm/N, which is slightly less than theoretically predicted. We chose to limit the applied force to 215 N to remain within the substrate range of elastic strain (stress, ~170 MPa; expected strain, <2.5‰) and to ensure full transmission of the applied force to the filter. For such a value we recorded a spectral shift of ~1 nm, which corresponds to more than two 100-GHz-spaced DWDM channels. We recorded at the same time (see Fig. 3) a 10% decrease of the transmission of the filter as well as a slight increase (4%) in its FWHM value.

We have demonstrated here without ambiguity the shift toward higher wavelengths of a classic DWDM filter loaded by a uniform uniaxial compressive force. The sensitivity of this shift is ~60% of the theoretical sensitivity calculated by a simple tensor model. This difference may have several origins, such as lack of accuracy in the thin-film elastic and elasto-optic coefficients of some layers of the filter. However, we stress, as noted for thermal behavior, that we reach a correct order of magnitude when the fused-silica parameters are used to predict the behavior of the single equivalent layer.

Practical implementation of this tuning scheme can be achieved with the help of piezoelectric ceramics, which permit forces as high as several hundreds of newtons to be applied to extensive and compressive modes. One can easily explore various designs, either by gluing the edge of a standard DWDM filter onto a ring-shaped ceramic or by placing both the filter and the ceramic into a square dedicated holder with tight manufacturing tolerances. In both cases the expansion of the ceramic induces the required compressive stress of the filter. We can also use special DWDM filters with disk shapes inserted into a ring-shaped ceramic such that the compressive force can be applied directly or through a thin glue layer.

Another attractive way to tune the filters can be by use of special substrates that have large piezoelectric coefficients. The application of an electric field upon such a substrate through dedicated electrodes induces a change in the physical dimensions of this substrate, and the result is a change in the central wavelength of a thin-film filter deposited upon its surface. The main problem connected with such a design lies in the choice of the material, which must be at the same time efficient, transparent, and well adapted to passive stabilization of the spectral properties of the filter with respect to temperature changes.

As a conclusion, it is important to stress that the effect that we described is similar to the spectral shift of an axially strained fiber Bragg grating but exhibits some attractive properties such as compatibility with thin-film NBPFs, the athermal behavior provided by the substrate dilatation, and a geometry that is well suited to the implementation of transverse stresses.

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