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Double coherent solid-spaced filters for very narrow-bandpass filtering applications

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Abstract

We report in this paper the study of a double coherent solid-spaced Fabry–Perot filter. The utilization of thick spacers enables to take advantage of their high optical quality and to use simple broad-band dielectric mirrors. Such single cavity filters are easy to manufacture and exhibit very low absorption and scattering levels. In a preliminary demonstration phase, the adjustement of the air gap thickness insuring the coherent coupling of both filters is done with a piezoelectric actuator. Experimental results concerning a double coherent solid-spaced filter centered at 1.56 μm with a maximum transmission of 98% and a full-width at half-maximum of 0.5 nm are given. The possible improvements of such components are discussed.

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Keywords: Thin film filter; DWDM; Solid-spaced filter

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1. Introduction

The continuous development of the telecommunications and its endless ask for an increasing of network capacity since the beginning of the 1990s has led to the use of the wavelength division multiplexing (WDM) technique where several wavelengths or channels can propagate through the same monomode fiber. Nowadays, it is possible to have information rate achieving 1 Terabits/s, combining more than 100 channels (separated by 0.8 nm for a 100 GHz grid and soon, by 0.4 nm for a 50 GHz grid) at 10 Gbits/s each one. For these applications, thin-film interference filters (TFF) are of great interest because they provide with efficient solutions for the passive wavelength selection needed by the routing of the optical signals (multiplexing, demultiplexing, add and drop, etc.). By using high quality deposition techniques like ion-assisted deposition (IAD) or ion beam sputtering (IBS), we can manufacture Fabry–Perot filters, made of several spacers (or cavities) sandwiched between two mirrors. The reduction of the

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channel spacing requires narrow-band interference filters with a flat and rectangular profile, with a small bandwidth, low insertion loss and a high rejection for adjacent channels (typically −25 dB). But, one of the major drawback of these components is the high number of layers which must be deposited on the substrate (usually more than 100). Thus, the manufacturing time of 50 GHz WDM filters is penalizing and errors can appear because of the variation of the sensitivity of the transmitted optical monitoring signal during the coating process. Moreover, losses due to absorption and scattering, particularly in the spacer region where the electric field is intense, introduce some limitations in the performances of these TFF.

To circumvent these manufacturing difficulties, we propose to use thick spacers of high optical quality (planeity and roughness, parallelism, homogeneity) and also to reduce the number of deposited layers to a small value (typically less than 20). The work presented in this paper describes the performances of two 50 GHz WDM solid-spaced Fabry–Perot using broadband dielectric mirrors (five layers) and two thick spacers whose optical thicknesses (of the order of 100 μm) are different to achieve automatically the filtering of the adjacent channels. It has to be noted that it exists alternative ways to achieve small bandwidth; for example, one can manufacture narrow-band interference dielectric filters with unconventional spacer layers [1].

2. Filter design

There are two ways to manufacture Fabry–Perot TFF [2,3]. The first one consists in depositing all the layers (spacer and mirrors) on a substrate (generally made of glass). We name these filters all-deposited filters. The optical thickness of the spacer must be a multiple of $\lambda/2$, λ being the center wavelength of the filter. The second method, applied in this paper, consists in depositing the mirrors on both sides of a polished wafer that will replace the spacer in the resulting filter (called solid-spaced filter or SSF).

The transmission of a Fabry–Perot SSF is a discrete channel spectrum and the wavelengths corresponding to the successive maximum transmission are given by $\lambda_k = 2ne/k$ for normal incidence [4], where n and e are the index and the thickness of the spacer, respectively, and k is an integer. The spectral spacing between two successive maximum transmission wavelengths λ_k and λ_{k+1} is called the free spectral range (FSR) and is given by $FSR = \lambda_k \lambda_{k+1}/2ne$.

For WDM applications, filters with a flat and rectangular transmission window and high rejection are required; then, it is clear that we must consider multiple cavity SSF, the cavities having different FSR (i.e., different spacer optical thickness) and coinciding at a unique particular wavelength. This appropriated difference of optical thickness provides with an auto-filtering scheme which limits the presence of unwanted peaks in the transmission spectrum. A good candidate for our spacers is fused silica (SiO_2), a classical optical material for which the polishing process is well controlled and with high optical performances (low scattering and absorption levels). The mechanical thickness chosen is between 100 and 150 μm. With such thicknesses, and considering a 50 GHz filter, the dielectric mirrors should be composed only of five quarter-wave layers alternatively of low (indicated as L) and high (H) refractive index. A quarter-wave layer is a layer whose optical thickness ne (n is the refractive index of the layer and e its thickness) verifies $ne = \lambda/4$ where λ is the center wavelength of the filter. The final design of the double coherent SSF is air/SSF1/air/SSF2/air where SSF1 stands for HLHLH/spacer1/HLHLH and SSF2 stands for HLHLH/spacer2/HLHLH. The optical thickness of the spacers are 402L (spacer 1 whose optical thickness is $ne = 402\lambda/4$) and 540L (spacer 2 whose optical thickness is $ne = 540\lambda/4$), respectively, and their refractive index is 1.44. The broadband dielectric mirrors HLHLH are composed alternatively of Ta_2O_5 ($n_{Ta_2O_5} = 2.09$ at 1.56 μm) and SiO_2 ($n_{SiO_2} = 1.46$ at 1.56 μm). It remains between both filters a residual air layer called the adaptation layer which coherently couples the filters when its optical thickness is quarter wavelength. We show in Fig. 1 (bold line) the theoretical transmissions of the double coherent SSF on a linear (a) and a dB (b) scale. The center wavelength provided by both

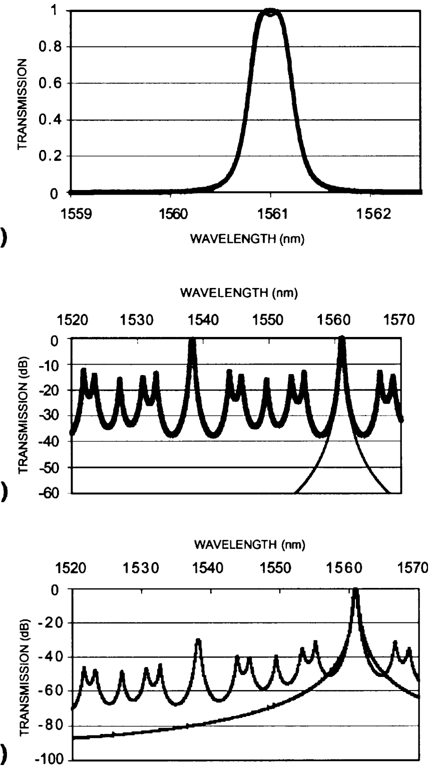

Fig. 1. Theoretical spectral response for a double coherent SSF (bold lines) and an all-deposited filter (filled lines). (a) Transmission with respect to the wavelength (linear scale); (b) transmission with respect to the wavelength (dB scale); and (c) theoretical spectral response for a double coherent SSF with a blocking filter (bold line) and an all-deposited filter (filled line) on a dB scale with respect to wavelength.

spacers' optical thicknesses is 1560.86 nm and the transmission reaches $T_{\max} = 1$ with a matched air gap. The spectral full-width at half-maximum (FWHM) is 0.457 nm. The residual transmission level (RTL) is between −12 dB (for the adjacent channels) and −37 dB (directly at the basis of the main peak) for the whole C-band (1520–1570 nm) except near 1538.4 nm where it is only −0.3 dB. At this particular wavelength, the optical thicknesses of the spacers coincide once again.

As a comparison, we also show in Figs. 1((a) and (b), filled line) an all-deposited double cavity filter on a glass substrate ($n_s = 1.52$) with the same materials. A similar FWHM leads to consider the following design: air/(HL)^{7}H/14L/H(LH)^7/L/(HL)^{7}H/14L/H(LH)^7/substrate. The number of deposited layers is quite important (63) and the total mechanical deposited thickness is 21.2 μm. Compared with the double coherent SSF (twice five layers on each thick spacer, i.e., a total of 20 layers and a total mechanical deposited thickness of 4.4 μm), the deposition time, approximately proportional to the mechanical thickness deposited, must be about five times higher. On the other hand, the rejection outside the transmission window is better than for our structure. A wide band-pass blocking filter is a solution to reach a better rejection level. In Fig. 1(c), we present the spectral response of the double coherent SSF incoherently associated with a blocking filter whose design will be detailed in part 4. The number of layers is then 40. For comparison, the spectral response of the all-deposited double cavity filter is also depictured. In both cases, the FWHM is the same and the rejection is better than −30 dB in the whole C-band, which is sufficient for WDM applications. Another solution to improve the rejection level consists in increasing the number of cavities. This will also be discussed in part 4.

3. Experimental demonstration

The manufacture of a double coherent SSF can be separated into three steps: the precise characterization of both wafers with the determination of the optical thickness at the center wavelength, the coating of broadband dielectric mirrors on both sides of the wafers, and finally, the rigorous coupling of both single cavity filters with the adjustment of the air gap (adaptation layer) thanks to a piezoelectric translator.

The selected wafers are made of fused silica and present a nominal thickness, given by the manufacturer, of 107 and 145 μm, respectively. The precise determination of thickness, refraction index and optical thickness is achieved by interferometric measurements between front and rear sides of the wafers at normal incidence. We use a tunable laser source EXFO FLS-2600 emitting in the C-band (1520–1570 nm) with a wavelength repeatability of about 10 pm. The laser beam is directed toward the wafer with a monomode fiber ended by a LightPath™ pigtailed collimator. The beam waist (about 250 μm) is located on the wafer surface. These working conditions are similar to those met in commercial systems. Then, the transmitted light is collected with an identical collimator and a monomode fiber connected to an InGaAs photodiode followed by a low noise current amplifier and a 16 bits digital to analog converter. The source and the measurements are computer controlled.

The whole transmitted spectrum measured in the C-band enables to determine by a least squares method the refractive index and the thickness. Optimized results provide a refractive index of $n = 1.443$ (supposed constant in the C-band range), and a measured thickness of 108.7 and 146.0 μm, respectively, for the analysis zone. The same technique allows us to measure the thickness distribution (mapping) of the wafers. For our purpose, we need very plane-parallel wafers. Our measurements give a parallelism of about 3 arc-second. Moreover, standard wafers with 1 arc-second parallelism are now easily available with both-side polishing techniques. For a 3 arc-second wafer illuminated with a standard gaussian beam for optical telecommunications (waist of 250 μm) the theoretical maximum transmission is reduced of less than 2% for 50 GHz filter designs.

With these particular values (108.7 and 146.0 μm), both optical thicknesses are exactly multiple of the half wavelength at $\lambda_0 = 1560.86$ nm. The existence of such a coincidence wavelength, called center wavelength, is crucial for the manufacture of a double coherent SSF.

The dielectric mirrors coated on both sides of the wafers are identically five quarter-wavelength layer ones, centered at 1561 nm, with alternatively Ta_2O_5 and SiO_2. The deposition process is IAD, with an in situ optical monitoring process. The same experimental setup as described above provides the optical characterizations of both SSF. We have plotted on Figs. 2(a) and (b) the measured transmission spectra. One can note at first the high level of the maximum transmission (99.9% for filter 1 (108.7 μm thick, bold line) and 98.9% for filter 2 (146.0 μm thick, filled line) at 1560.86 nm, and the sharpness of the transmission window, even with such broadband mirrors (the spectral FWHM is about 0.79 and 0.55 nm, respectively). The difference with the theoretical maximum transmission (100%) can be explained by the impact of errors of parallelism between both faces of the wafers (3 arc-second) existing over the diameter of the incident beam waist ($2w_0 = 500\,\mu$m). The RTL outside the transmission window reaches −16 dB.

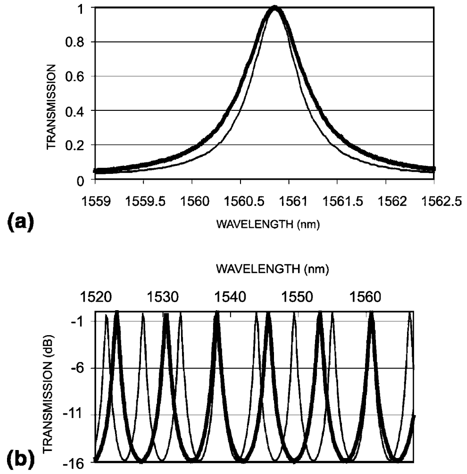

Fig. 2. SSF: experimental spectral response; (bold lines) filter 1; (filled lines) filter 2. (a) transmission with respect to the wavelength (linear scale) and (b) transmissions with respect to the wavelength (dB scale).

The coupling of both filters for a double coherent SSF is achieved by autocollimation between the different interfaces air/filters. The spacing between both components is roughly set to about 30 μm. This distance is small enough to throw off eventual resonance peaks due to the air gap. A piezoelectric translator (PT) of 0.7 μm/V sensitivity enables to adjust the air gap to a near quarter wavelength distance with the following procedure. The shape of the spectral transmission around the resonance peak (1560.86 nm) strongly depends on the optical thickness of the air gap. The optimal shape, which corresponds to a square shape, is obtained when the thickness of the air gap is an odd multiple of a quarter wavelength. The adjustment is then obtained by small displacements of the PT until the spectral response is optimized.

The measured spectral transmission after optimization of the air gap thickness is depicted in Fig. 3. The center wavelength remains the same, at 1560.86 nm. The maximum transmission is 98.1%

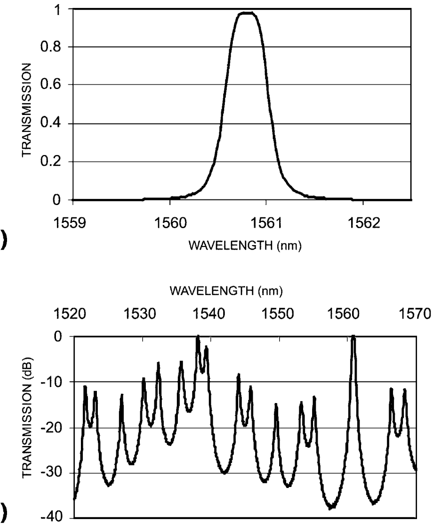

Fig. 3. Double coherent SSF: experimental spectral response. (a) Transmission with respect to the wavelength (linear scale) and (b) transmission with respect to the wavelength (dB scale).

due to spacer non-parallelism as shown in part 2. The spectral FWHM is about 0.47 nm, which is closed to the theoretical predictions (0.45 nm). The RTL reaches −14 dB for the adjacent channel (at 1553.3 nm), −9 dB for the next channel (at 1544.1 nm). At 1538.2 nm, where another coincidence occurs, the RTL is only of −0.3 dB. Note that the agreement with theoretical calculations (Fig. 1, filled line) is deteriorated when the wavelength is below 1545 nm. Reverse engineering simulations show that a relative random errors between 0% and 5% on the mirror layer thicknesses, which is plausible, could explain the difference.

An important characteristic of narrow-band-pass TTF is its temperature stability of center wavelength (TSCW). A change in temperature makes the center wavelength of the filter shifts. This shift has been studied by H. Takashashi [5]. Utilizing this model, we find that each simple cavity filter has a center wavelength sensitivity of about 12 pm/°C. The center wavelength sensitivity of the double cavity filter is identical. One can note that if we take into account only the temperature dependance of the refractive index of the spacer, we find a sensitivity of about 11 pm/°C. Compared to the WDM requirement (sensitivity less than 1 pm/°C), this value seems too high. Nonetheless, this property could provide a method to tune the filter.

4. Discussion

One major prospect is to increase the filtering efficiency on the whole ITU grid (or C-band). To reach this goal, we consider two possibilities: the utilization of a blocking filter and the increase of the number of cavities. Both possibilities increase the complexity and the cost of the resulting filter.

Let us first consider the case of a blocking filter. This filter, separately manufactured, is incoherently added with the double cavity SSF made above. Thus, the global transmission is the product of the transmission of each one. We have theoretically studied the following all-deposited double cavity blocking filter: air/$(HL)^4$H/10L/H$(LH)^4$/L/$(HL)^4$H/10L/H$(LH)^4$/substrate. The substrate is made of glass ($n = 1.52$); the high and low index materials are the same as in part 2. With this filter centered at 1560.86 nm, we could be able to reach a RTL $\leqslant -30$ dB for the whole C-band. Thus, we have only one peak centered at 1560.86 nm with a maximum transmission and a FWHM unchanged. But, the manufacture of such a blocking filter is quite difficult and long (11 μm coated approximately). Therefore, we also have studied the possibility to make a blocking filter with a reduced number of layers; it implies that the refractive index contrast is more pronounced. So, let us replace the Ta_2O_5 layers by Si layers ($n_{Si} = 3.5$). The following single cavity blocking filter also permits to have a RTL $\leqslant -30$ dB for the whole C-band: air/$(HL)^2$H/10L/H$(HL)^2$/substrate. The total coated thickness is now only 4.4 μm. The development of such a component is currently in progress in our laboratory. It has to be noted that in both cases the blocking filter must be treated on rear side with an anti-reflection coating to avoid retro-reflection toward the filter.

Another possibility to eliminate ripples is to increase the number of cavities. We can consider at least a triple cavity filter. Theoretically, a triple cavity filter with spacers of different thicknesses (250L, 180L and 280L corresponding to 67.1 μm, 48.3 and 75.2 μm, respectively), seven layers mirrors and two air gaps of about 30μm permits to attain a −20 dB RTL on the adjacent channels. It is clear that the multiplication of the cavities number will enable to achieve a −30 dB RTL on the whole ITU grid (a five cavities filter for example).

The other prospect for our multiple coherent SSF is the possibility to contact two simple SSF in order to satisfy miniaturization constraints applicable to WDM components. The adhesion of two massive wafers are well known. Austin [6] has mentioned a method which permits to optically contact a coated surface with an uncoated wafer. In our case, the optical contact has to be done between two coatings. Even if the requirements on the flatness, the smoothness and the cleanliness of the surfaces seem very restrictive [7,8], this method is technically feasible [9,10].

5. Conclusion

We have shown the feasibility of a double coherent SSF with autofiltering properties for the ITU grid. The first experimental results are in good agreement with theoretical calculations. Preliminary, the air gap that behaves as an adaptation layer is controlled with a piezoelectric translator. We obtain a maximum transmission of 98% and a FWHM of 0.45 nm. Moreover, we can obtain filters with high performances in a reduced time taking advantage of the fact that only mirrors with few number of layers are necessary. In order to realize the filtering of the whole ITU grid, we should consider a multiple coherent autofiltering SSF with at least three cavities. The utilization of a blocking filter is also conceivable. The manufacture of a tunable SSF for WDM frequency grid seems possible if the spacer is an active material (piezoelectric or electro-optic like $LiNbO_3$).

Acknowledgements

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