Achievement of Arbitrary Bandwidth of a Narrow Bandpass Filter

Cheng-Chung Lee[1], Sheng-Hui Chen[1], Chien-Cheng Kuo[1] and Ching-Yi Wei[2]

[1]*Department of Optics and Photonics/ Thin Film Technology Center, National Central University 320, Taiwan*
[2]*Apogee Optcom, Tainan 744, Taiwan*
**Corresponding author: cclee@dop.ncu.edu.tw*

Abstract: By adjusting the coating parameters to vary the refractive index of the thin film material, we are able to fine tune the bandwidth of a narrow bandpass filter to an arbitrary value. The relation between the varied index Δn and the maximum arbitrary bandwidth was analyzed. A 4-skip-0 bandpass filter for a 100 GHz DWDM system was designed and fabricated. In addition, the relation between the tolerance of the index and the bandwidth was also analyzed to avoid broadening or narrowing the bandwidth. The final results showed that the arbitrary bandwidth met the requirements very well.

OCIS codes: (060.4230) Multiplexing; (310.4165) Multilayer design; (310.6845) Thin film devices and applications.

References and links

1. C. C. Lee, S. H. Chen and C. C. Kuo, "Fabrication of dense wavelength division multiplexing filters with large useful area," Proc. SPIE **6286**, 62860E (2006).
2. H. A. Macleod, "Tutorial on the design of telecommunication filters," in *Conference on Optical Interference Coatings*, Technical Digest (CD) (Optical Society of America, 2001) paper PWC1.
3. P. Baumeister, "Bandpass Filters for Wavelength Division Multiplexing-Modification of the Spectral Bandwidth," Appl. Opt. **37**, 6609-6614 (1998).
4. R R. Willey, "Achieving narrow bandpass filters which meet the requirements for DWDM," Thin Solid Films **398**, 1-9 (2001).
5. P. Baumeister, "Design of a wavelength-division multiplexing bandpass with quasi-Chebyshev spectral shape," Appl. Opt. **40**, 1132- 1137 (2001).
6. H. A. Macleod, *Thin-Film Optical Filters, 3rd Ed.*, (Institute of Physics Publishing, 2001), Chap. 7.2.2.

---

1. Introduction

A narrow band pass filter with specified bandwidth is extremely important and not easy to achieve, particularly for optical communications applications [1, 2]. The design of the narrow bandpass filter described in this paper is based on a Fabry-Perot interferometer [3-5]. It consists of two identical parallel reflecting stacks (a and b) spaced apart a distance, called a "spacer". According to multiple-beam interference, the transmittance of the passband can be expressed as Eq.(1):

$$T = \frac{(1\text{-}R_a)(1\text{-}R_b)}{\left[1-(R_aR_b)^{1/2}\right]^2}\cdot\left[\frac{1}{1+F\sin^2\phi}\right], \quad (1)$$

where,. $F = \frac{4(R_aR_b)^{1/2}}{\left[1-(R_aR_b)^{1/2}\right]^2}$, $\phi = \frac{2\pi}{\lambda}nd - \frac{\phi_a+\phi_b}{2} = m\pi$. R_a, R_b, ϕ_a , and ϕ_b are the reflectance and phase shift of the reflecting surfaces a and b, respectively. n and d are the refractive index and the physical thickness of the spacer, respectively. λ is the wavelength of the incident light, and m=0, 1, 2, … is the order of the spacer layer. Normally the pass

#86976 - $15.00 USD Received 28 Aug 2007; revised 24 Oct 2007; accepted 31 Oct 2007; published 2 Nov 2007

bandwidth (BW) is defined as the width of the band measured at the half peak transmittance. For all dielectric narrow bandpass filters with symmetrical reflecting surfaces, the BW can be expressed as follows [6]:

$$\mathrm{BW_H(m,\,x)} = \frac{1}{m}\left(\frac{n_\mathrm{L}}{n_\mathrm{H}}\right)^{2x}\frac{4n_\mathrm{S}}{\pi n_\mathrm{H}}\lambda_c\left(\frac{n_\mathrm{H}-n_\mathrm{L}}{n_\mathrm{H}-n_\mathrm{L}+n_\mathrm{L}/m}\right) \text{ (for the high-index spacer)}, \tag{2}$$

$$\mathrm{BW_L(m,\,x)} = \frac{1}{m}\left(\frac{n_\mathrm{L}}{n_\mathrm{H}}\right)^{2x}\frac{4n_\mathrm{S}}{\pi n_\mathrm{L}}\lambda_c\left(\frac{n_\mathrm{H}-n_\mathrm{L}}{n_\mathrm{H}-n_\mathrm{L}+n_\mathrm{L}/m}\right) \text{ (for the low-index spacer)}, \tag{3}$$

where n_H, n_L and n_S are the refractive indices of the high-index material, low-index material and substrate, respectively; x is the layer number of the high-index material in the reflecting stack and λ_c is the central wavelength of the filter. Since m and x are integers, the BW is not continuously adjustable. In other words, it is impossible to design filters of arbitrary BW with Fabry-Perot structure when the coating materials are specified. The purpose of this article is to find a relation to use to design a bandpass filter with an arbitrary BW, including its conditions and limitations. This will provide a good reference for people designing bandpass filters. Then a fabrication method by controlling the Ar flow of the ion source in an electron beam gun (E-gun), with an ion-assisted deposition process is described to realize the theoretical design.

2. Pass-bandwidth Analysis

To design a square top 4 skip 0 filter, multiple cavities are needed. Figure 1 shows some multiple cavity filters. It shows that the BW is narrower when using a high-index material as a spacer than when using a low-index material. It is wider when reducing the order of m or x. However the BW cannot be arbitrary. There is no solution between the locations of the colored curves shown in Fig.1. To achieve an arbitrary BW, the refractive indices of the coating materials must be changed.

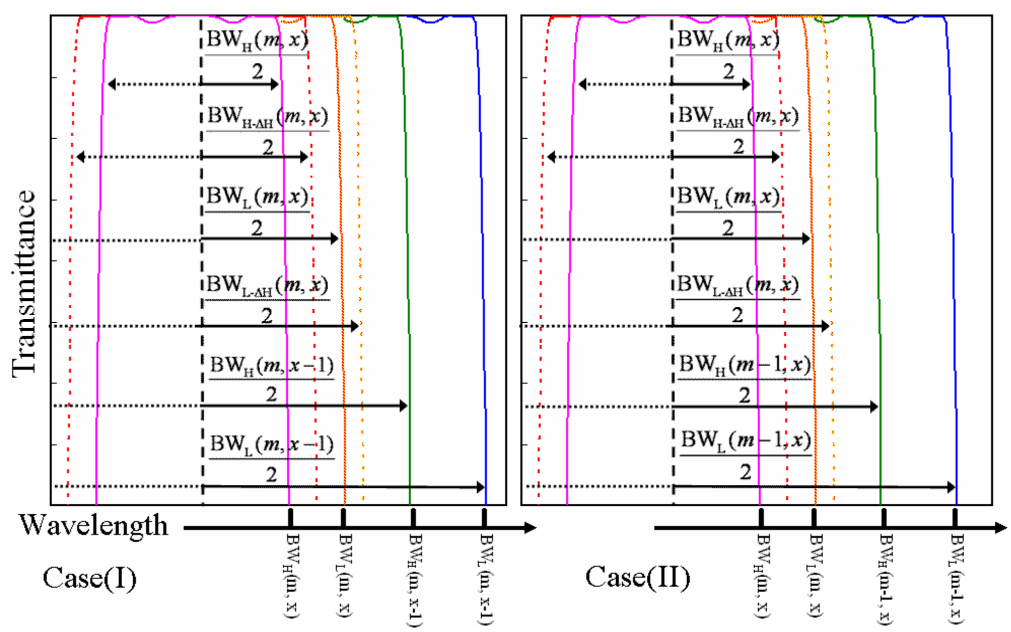

Fig. 1. Solutions of pass bandwidths for different spacer materials, orders m and x

To determine the conditions of the arbitrary BW for all dielectric narrow bandpass filters, we assume that the high-index material is Nb_2O_5 with n_H = 2.25 at a wavelength of 1550 nm

#86976 - $15.00 USD Received 28 Aug 2007; revised 24 Oct 2007; accepted 31 Oct 2007; published 2 Nov 2007

and the low-index material is SiO_2 with $n_L = 1.45$ at the same wavelength. n_H can be varied within a certain range by changing the parameters of the coating process. Two cases are analyzed to see the variation range of n_H to achieve the condition of an arbitrary BW.

Case (I): varying the index to meet a different order x:

For a certain order x, to have a continuous change of the BW, the variation of n_H, Δn, must satisfy Eqs. (4) and (5) as can be seen from Eqs. (2), (3) and Fig.1.

$$BW_{H\text{-}\Delta H}(m, x) = BW_L(m, x) \tag{4}$$

$$BW_{L\text{-}\Delta H}(m, x) = BW_H(m, x\text{-}1) \tag{5}$$

where -ΔH in the BW means that n_H is reduced by Δn. That is, $n_{H\text{-}\Delta H} = n_H - \Delta n$. Evaluating Eqs.(4) and (5) we have

$$\frac{1}{m}\left(\frac{n_L}{n_{H\text{-}\Delta H}}\right)^{2x}\frac{4n_S}{\pi n_{H\text{-}\Delta H}}\lambda_c\left(\frac{n_{H\text{-}\Delta H}-n_L}{n_{H\text{-}\Delta H}-n_L+n_L/m}\right)=\frac{1}{m}\left(\frac{n_L}{n_H}\right)^{2x}\frac{4n_S}{\pi n_L}\lambda_c\left(\frac{n_H-n_L}{n_H-n_L+n_L/m}\right).$$

$$\frac{1}{m}\left(\frac{n_L}{n_{H\text{-}\Delta H}}\right)^{2x}\frac{4n_S}{\pi n_L}\lambda_c\left(\frac{n_{H\text{-}\Delta H}-n_L}{n_{H\text{-}\Delta H}-n_L+n_L/m}\right)=\frac{1}{m}\left(\frac{n_L}{n_H}\right)^{2x\text{-}2}\frac{4n_S}{\pi n_H}\lambda_c\left(\frac{n_H-n_L}{n_H-n_L+n_L/m}\right)$$

Compared with n_H, Δn is small enough to be ignored. Thus we can obtain

$$\Delta n \approx n_H\left[1\text{-}\left(\frac{n_L}{n_H}\right)^{\frac{1}{2x+1}}\right] \tag{6}$$

$$\Delta n \approx n_H\left[1\text{-}\left(\frac{n_L}{n_H}\right)^{\frac{1}{2x}}\right]. \tag{7}$$

Case (II): varying the index to meet a different order m:

For a certain order m, to have continuous change of the BW, the variation of n_H, Δn, must satisfy Eqs. (8) and (9) as follows:

$$BW_{H\text{-}\Delta H}(m, x) = BW_L(m, x) \tag{8}$$

$$BW_{L\text{-}\Delta H}(m, x) = BW_H(m\text{-}1, x) \tag{9}$$

Evaluating Eqs.(8) and (9) we have

$$\frac{1}{m}\left(\frac{n_L}{n_{H\text{-}\Delta H}}\right)^{2x}\frac{4n_S}{\pi n_{H\text{-}\Delta H}}\lambda_c\left(\frac{n_{H\text{-}\Delta H}-n_L}{n_{H\text{-}\Delta H}-n_L+n_L/m}\right)=\frac{1}{m}\left(\frac{n_L}{n_H}\right)^{2x}\frac{4n_S}{\pi n_L}\lambda_c\left(\frac{n_H-n_L}{n_H-n_L+n_L/m}\right)$$

$$\frac{1}{m}\left(\frac{n_L}{n_{H\text{-}\Delta H}}\right)^{2x}\frac{4n_S}{\pi n_L}\lambda_c\left(\frac{n_{H\text{-}\Delta H}-n_L}{n_{H\text{-}\Delta H}-n_L+n_L/m}\right)=\frac{1}{m\text{-}1}\left(\frac{n_L}{n_H}\right)^{2x}\frac{4n_S}{\pi n_H}\lambda_c\left(\frac{n_H-n_L}{n_H-n_L+n_L/m}\right)$$

Compared with n_H, Δn is small enough to be ignored. Thus we can obtain

#86976 - $15.00 USD Received 28 Aug 2007; revised 24 Oct 2007; accepted 31 Oct 2007; published 2 Nov 2007

$$\Delta n \approx n_H \left[1 - \left(\frac{n_L}{n_H} \right)^{\frac{1}{2x+1}} \right] \tag{10}$$

$$\Delta n \approx n_H \left[1 - \left(\frac{m-1}{m} \cdot \frac{n_H}{n_L} \right)^{\frac{1}{2x}} \right] \tag{11}$$

From the above analysis, we can see that the Δn value of Eq. (7) is always larger than Δn of Eq. (6). So, the design rule is chosen to follow Eq.(7) in Case (I). Similarly, Δn of Eq. (11) is always larger than Δn of Eq. (10). The design rule is then chosen to follow Eq.(11) in Case (II). Considering the results of Case (I) and Case (II), Δn in Eq. (11) is larger than Δn in Eq. (7). This means that we can design an arbitrary BW of a filter with a smaller variation of the index by following the rule of Case (I) rather than by following Case (II). The maximum adjustable range of the arbitrary BW will be for m=1 of Eq. (3) with a high refractive index n_H-Δn. It can be shown that the variation of the index Δn with the maximum arbitrary bandwidth is given by Eq. (12) and Fig. 2.

$$BW_{max}(\Delta n) \approx \left(\frac{n_L}{n_H} \right)^{2x-1} \frac{4n_S}{\pi n_H} \lambda_c \left(\frac{n_H - n_L}{n_H - n_L + n_L / m} \right), \text{ where } x = \frac{\ln\left(\frac{n_L}{n_H} \right)}{2 \cdot \ln\left(1 - \frac{\Delta n}{n_H} \right)} \tag{12}$$

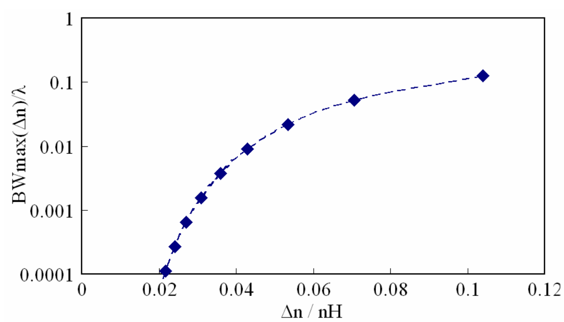

Fig. 2. Relation between the variation of the index Δn and the maximum arbitrary bandwidth

3. Filter Design and Fabrication

When designing a narrow bandpass filter, sometimes we find that the BW cannot meet the specification no matter what values of the orders x or m are chosen. For example, a 4-skip-0 bandpass filter for a 100 GHz DWDM system for optical communication. Figure 3 shows that there are 4 100 GHz of channels within the passband and the channels beside the four channels are blocked by its stopband. The specifications are listed in Table 1. When using Nb_2O_5, n_H =2.25 and SiO_2, n_L =1.45 as the high and low refractive indices materials to design the filter, designs A and B shown in Table 1 can meet part of the specifications. Design A is a 9-cavity design with m=2, x=6, and low-index material spacer as follows,

Glass/ $[(HL)^5\ 2H\ (LH)^5L]$ $[(HL)^5\ H2LH\ (LH)^5L]$ $[(HL)^5\ H4LH\ (LH)^5L]^5$ $[(HL)^5\ H2LH\ (LH)^5L]$ $[(HL)^5\ 2H\ (LH)^4L\ 0.69H\ 0.73L]$ /Air.

The central 5 cavities in Design A is the basic structure. The adjoining two cavities on both sides of the central cavities are needed to reduce the ripple in the passband. The stop bandwidth of Design A is narrow enough to meet the requirement. However the pass

#86976 - $15.00 USD Received 28 Aug 2007; revised 24 Oct 2007; accepted 31 Oct 2007; published 2 Nov 2007

bandwidth is too narrow to meet the specification. If we broaden the bandwidth by reducing the order x, we have Design B. It is a design with m=3, x=5; the high-index material spacer is as follows,

Glass/ $[(HL)^5\ 2H\ (LH)^5L]\ [(HL)^5\ 4H\ (LH)^5L]\ [(HL)^5\ 6H\ (LH)^5L]^5\ [(HL)^5\ 4H\ (LH)^5L]\ [(HL)^5\ 2H\ (LH)^4L\ 1.29H\ 1.31L]$ /Air.

Unfortunately, although the pass bandwidth is wide enough, the stop bandwidth is too wide to meet the specification. The problem can be resolved by adding more cavities in the design. But the ripple and the total thickness will then also increase. Another way to resolve the problem is to adjust the index of the material to obtain an arbitrary BW filter. Based on Design A, we changed the index of Nb_2O_5 from 2.25 to 2.22 and obtained Design C. Table 1 shows that both the pass bandwidth and the stop bandwidth meet the specification.

Design C is a symmetrical layer structure which is a fairly stable design for fabrication, although it is not as robust as a design having identical spacers. In addition, all of the spacers are low index material except the first and the last spacers. That means that we try to avoid using a high index material in the spacer layer, since the design with low index spacers has a higher production yield than the design with high index spacers.

Table 1. Requirements and designs of a 4-skip-0 bandpass filter

Filter Specs	**Requirement**	**Design A**	**Design B**	**Design C**
Center Wavelength (nm)	ITU 100GHz grid +50GHz	---	---	---
Pass bandwidth (at -0.3dB) (nm)	>2.8	2.45	3.10	2.85
Stop bandwidth (at -25dB) (nm)	<3.6	3.08	3.70	3.54
Passband Ripple (dB)	< 0.3	0.11	0.17	0.11

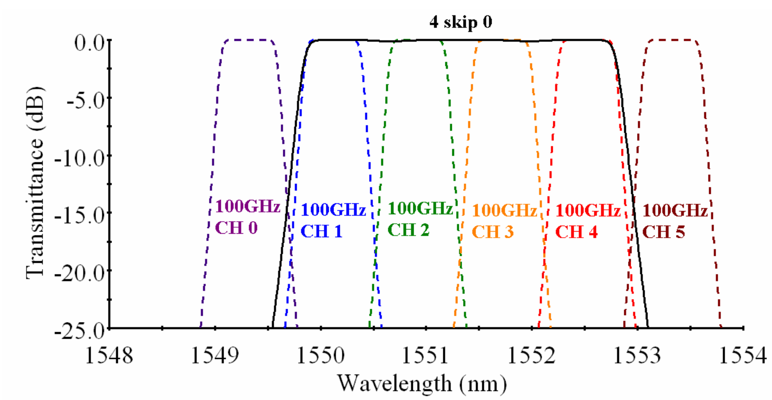

Fig. 3. Sketch of the 4-skip-0 bandpass filter with 100GHz DWDM filters

To achieve Design C, the refractive index of Nb_2O_5 must be changed from 2.25 to 2.22. According to Eqs (2) and (3), when the high-index material has a variation Δ, the bandwidth will be modified from BW to BW' and the relation as follows

$$BW' = BW(1+2x\Delta/ n_H) \tag{13}$$

That means the tolerance in index will be enlarged 2x times in bandwidth. Comparing the results of Design C with the specifications in Table 1, the tolerance of bandwidths is only +/-1.8%. So, the tolerance of the index should be within +/-0.18% for x=5 in Design C.

To control the index of Nb_2O_5 within the tolerance, a fabrication method was used that controlled the Ar flow of the ion source in an E-gun with an ion-assisted deposition process.

The ion source system was a 16 cm Kaufman-type ion source. When the ion source was filled with 40 sccm pure O_2 (99.999%) as the working gas, the refractive index of Nb_2O_5 was 2.25. If a little Ar (99.999%) was added to the working gas, the index of Nb_2O_5 was decreased. The experimental results are shown as the diamonds in Fig. 4. The error bars in Fig. 4 are all within +/-0.18% which meets the requirement of Design C. We can assume that the relation is linear, like the solid line in Fig. 4. Hence if we want to reduce the index of Nb_2O_5 to 2.22 the gas flow of Ar has to be controlled at about 2.05 sccm.

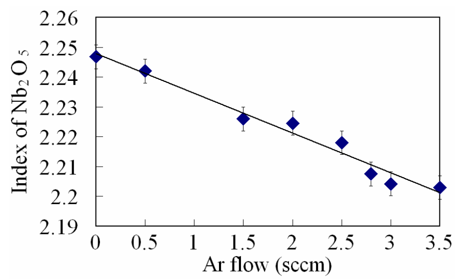

Fig. 4 Relation between the Ar flow rate in an ion source and the index of Nb_2O_5

4. Results and Discussion

We have derived the conditions for an arbitrary pass bandwidth for an all dielectric narrow bandpass filter. The arbitrary bandwidth can be achieved by varying the index of the thin-film material. The relation between the variation of the index Δn and the maximum arbitrary bandwidth has been analyzed. A 4-skip-0 bandpass filter was fabricated by controlling the Ar flow of an ion source in an E-gun in an ion-assisted deposition process. The index of Nb_2O_5 was reduced to 2.22 with an Ar flow of 2.05 sccm as required by Design C. The fabrication result is shown in Fig. 5. The pass bandwidth is about 2.81 nm; the stop bandwidth is about 3.56 nm and the ripple is about 0.197 nm. From the results, we can see the bandwidth of the all dielectric narrow bandpass filter can be varied easily by controlling the quantity of Ar flow of the ion source to meet the specification. Another important advantage is that the tolerance of the index variation by controlling the Ar flow can be small and very accurate to avoid broadening or narrowing the designed bandwidth. The final results show that it is easily possible to achieve an arbitrary bandwidth to meet the specification.

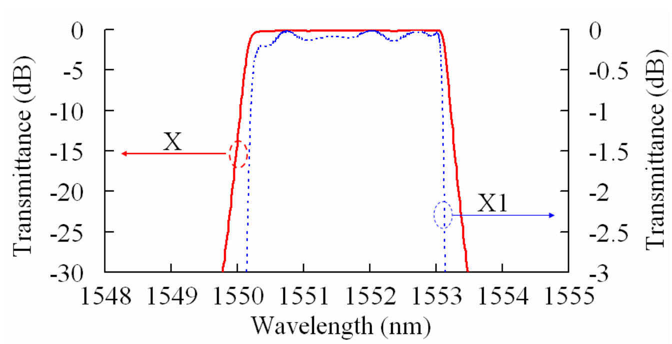

Fig. 5 Fabrication result for a 4-skip-0 bandpass filter

Acknowledgement

The authors thank the National Science Council of Taiwan for financially supporting the study under Contract Numbers NSC95-2221-E-008-115-MY3 and NSC96-2221-E-008-052-MY3.