Gain-Flattening Filters Using Dielectric Multilayer Thin Film

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ABSTRACT In wavelength-division multiplexing (WDM), which is fast emerging as mainstream technology to satisfy increased demand for fiber-optic communications, the erbium-doped fiber amplifier (EDFA) is a key device. Gain-flattening filters are used to produce flat gain characteristics within the bandwidth of the EDFA, and a number of methods have been proposed. The authors have developed a series of gain-flattening filter chips based on dielectric multilayer thin film, and by optimizing the thin film design, optical thickness control techniques and thin film deposition conditions to the requirements of the filters, have succeeded in producing gain-flattening filters for EDFAs with a gain of 13 dB, which have a flatness of 0.19 dB and an insertion loss of less than 0.1 dB.

1. INTRODUCTION

The demand in recent years for greater capacities and higher speeds in fiber-optic communications has led to the commercial implementation of wavelength-division multiplexing (WDM) technology in which optical signals of a number of different wavelengths are superimposed for transmission. The erbium-doped fiber amplifier (EDFA) serves as a key device in WDM systems. One of the advantages of the EDFA is that its bandwidth of amplification is comparatively wide, allowing the optical signals within the bandwidth to be batch-amplified, and recently its amplification bandwidth has been increasing.

In WDM systems the power deviation between the optical signals of different wavelengths results in a decrease in transmission distance and in the wavelength range of transmittance, requiring that EDFAs have a gain spectrum that is flat within the signal waveband. EDFAs, however, make use of the stimulated emission of erbium ions to amplify input signals, with the result that their gain spectra, reflecting the fine structure of the ion energy levels, are not flat but exhibit an asymmetrical two-peaked configuration within the amplification waveband. Normally this is compensated for by means of a gain-flattening filter; that is to say an optical filter having a loss profile that is the inverse of the gain spectra of the erbium-doped fiber is inserted into the EDFA, flattening the gain.

A number of proposals have been made relating to the technology used in gain-flattening filters, including the use of: etalon filters 1)-3), dielectric multilayer thin film filters 4), long-period fiber gratings 5), short-period fiber Bragg gratings 6), Mach-Zender silica waveguides 7), and split-beam Fourier filters 8). All of the above except the dielectric multilayer thin film filters must be combined with a number of components that have a periodic characteristic with respect to wavelength. Dielectric multilayer thin film filters, on the other hand, have the advantage that the loss profile can be obtained by interference within a single filter, and are therefore superior in terms of insertion loss, ease of manufacture and design freedom.

Their disadvantage is that obtaining the target loss profile with a dielectric thin film filter requires the precision deposition of more than 70 layers, a task that is beyond the capabilities of existing optical thickness control technology. Recently a high-precision thin film deposition system that can reoptimize the remaining layer thicknesses as deposition proceeds has been developed and made commercially available 9), but if the error that occurs exceeds a certain tolerance, the reoptimization is ineffective. A further problem remains in that it is necessary to keep precise track of the optical characteristics of the thin film during deposition.

In the present work it has been possible to provide a gain-flattening filter based on dielectric multilayer thin film technology by means of high-precision phase-predictive optical thickness control, without resort to the kind of thickness reoptimizing system referred to above. The present paper describes the optimized thin film design and the newly developed optical thickness control method, and reports results obtained from prototypes.

2. IMPROVEMENTS IN THIN FILM DESIGN AND DEPOSITION CONTROL

2.1 Thin Film Design Based on Thick Layer

There are broadly speaking two methods of obtaining a dielectric multilayer thin film filter having a high-precision loss profile: by increasing the designed tolerance; and by

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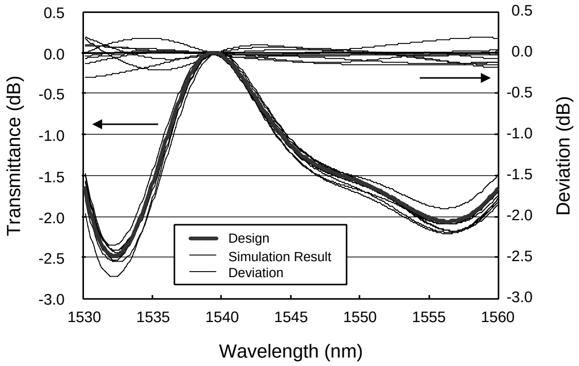


Figure 1 Typical simulations of gain-flattening filters. (10 iterations)

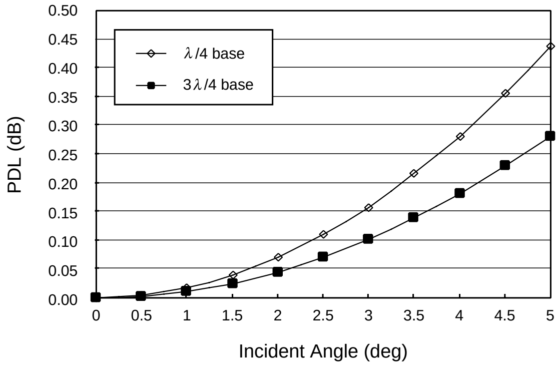


Figure 2 Dependence of PDL on incident angle for λ/4- and 3λ/4-based designs.

Table 1 Evaluation of multilayer thin film designs.

Base optical thickness	λ/4	3λ/4	5λ/4	7λ/4	9λ/4
Number of layers	69	42	32	26	22
Total optical thickness (where λ = 1550 nm)	15.5 λ	29.5 λ	38.1 λ	43.7 λ	47.7 λ
Optical thickness tolerance (base λ/4)	0.1 %	0.2 %	0.5 %	0.8 %	1.0 %
Refractive index tolerance	0.1 %	0.2 %	0.5 %	1.0 %	1.0 %

decreasing the optical thickness control error during deposition. First, we attempted to improve the former.

Structurally speaking a dielectric multilayer thin film consists of alternate layers of materials of high and low refractive indices, deposited onto a glass substrate. Generally, the reference wavelength, also known as the center wavelength, is set in the vicinity of the target loss profile and each layer of the thin film has an optical thickness of approximately one-quarter of the center wavelength.

The stack of layers of which the optical thickness is one quarter of the center wavelength has optical characteristics such that there is a cut-off region near the center wavelength and transmission bands on either side, so that optimization by means of non-linear fitting of the optical thickness of each layer makes it possible to approach the desired loss profile. Normally, gain-flattening filters are also designed by this method.

The cut-off band of a stack each layer of which has an optical thickness of one quarter of the center wavelength will appear in the vicinity of the center wavelength. This is because the length of the two-way optical path in each layer is one half of the center wavelength, as Bragg's Law makes clear. Similarly when the two-way optical path length in each layer is an odd multiple of one half of the center wavelength, a cut-off band occurs, in which case the optical thickness of each layer is an odd multiple of one quarter of the center wavelength. The optical characteristics of a stack each layer of which has an optical thickness that is an odd multiple of one quarter of the center wavelength will in the same way show a cut-off band in the vicinity of the center wavelength and transmission bands on either side.

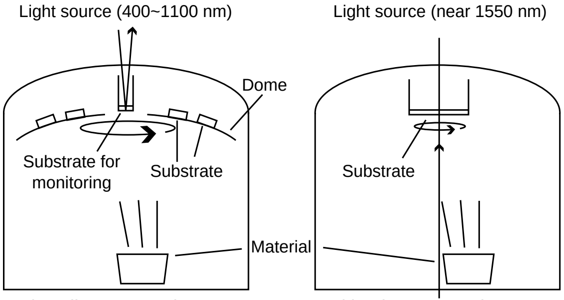
Using as initial values of each layer of a stack the 1st, 3rd, 5th, 7th and 9th multiples of one quarter of the center wavelength we designed the gain-flattening filter by optimizing using non-linear fitting, and compared them. 20 iterations of a simulation of the thin film deposition process were carried out applying a random optical thickness or refractive index error having a standard deviation, and the error level at which the maximum value of flatness exceeded 0.3 dB was established as the tolerance, where flatness is defined as the difference between the maximum and minimum values of deviation between the target loss profile and designed profile. Figure 1 shows typical simulations.

Table 1 shows the tolerance for each design. It can be seen that in designing a gain-flattening filter from a stack each layer of which has a greater optical thickness, the number of layers needed to obtain the same characteristic will be less. Also the greater the basic optical thickness the greater will be the tolerance in optical thickness and refractive index. On the other hand, whereas the greater the basic optical thickness the greater the total optical thickness of thin film, recent advances in thin film deposition equipment mean that this no longer presents a significant problem up to 50λ of total optical thickness, where λ is 1550 nm.

When the incident light is not normal to the thin film surface, the polarization-dependent loss (PDL) takes a finite value. Figure 2 shows the results of theoretical calculations for PDL for designs based in which the optical thickness is 1 and 3 times one quarter of the center wavelength. It can thus be seen that stacks each layer of which has a greater optical thickness will tend to have a lower value of PDL.

2.2 Direct Monitoring of Optical Thickness

Within the thin film deposition equipment there is a distribution of the material evaporation, so that film thickness will vary depending on its position in the equipment. When the deposition process is of high precision, even the discrepancies in thickness due to the position on the substrate can present problems. In the past, the indirect monitoring method generally used for optical thickness monitoring was to provide a substrate specifically for the optical thick-



a) Indirect transmittance monitoring system
b) Direct transmittance monitoring system

Figure 3 **Schematics of indirect and direct transmittance monitoring systems for optical thickness.**

ness monitor, in a position different from that of the substrate for thin film deposition, and to use a new monitoring substrate for each layer, but the need to keep accurate track of the film thickness distribution meant that this method was not suited to high-precision optical thickness control. In the thin film deposition equipment used in this work we adopted a direct monitoring system for optical thickness monitoring, providing direct monitoring of the part of the substrate on which it was desired to obtain the target loss profile. It is of the transmittance type, with the monitor light normal to the substrate. Figure 3 shows schematics of indirect and direct transmittance monitoring systems for optical thickness.

The optical thickness monitor controls optical thickness by taking advantage of periodic changes in the transmittance, where extremum appear in the transmittance for the deposition of each one quarter of the monitoring wavelength. Conventionally the optical thickness of the each layer was about one quarter of the center wavelength, so that the wavelength of the monitoring light was often only less than one half of the center wavelength. Normally the wavelength region of the target loss profile is in the neighborhood of the center wavelength, but since the refractive indices at the wavelength region of the target loss profile and the wavelength of the monitoring light are different, this can be a cause of thickness error even when consideration is given to wavelength dependence.

When the optical thickness is greater than 2/4 of the center wavelength, multiple transmittance extremum will appear even when the optical thickness monitoring wavelength is taken as the wavelength range of the target loss profile, so that highly accurate optical thickness control can be obtained even when the wavelength of the monitoring light is chosen from the wavelength range of the target loss profile. Using the thin film design based on thick layer described above, the optical thickness monitoring wavelength was chosen from the wavelength range of the target loss profile.

2.3 Phase-Predictive Optical Thickness Control

Let us take a moment to discuss briefly the theory of multilayer thin film [10]. When the angle of incidence is normal to the surface of a multilayer thin film, for the jth layer of the thin film, the characteristic matrix M_j will be as shown in Equation (1),

$$M_\mathrm{j} = \left\{ \begin{matrix} \cos g_\mathrm{j} & i \sin g_\mathrm{j} / n_\mathrm{j} \\ i n_\mathrm{j} \sin g_\mathrm{j} & \cos g_\mathrm{j} \end{matrix} \right\} \tag{1}$$

and g_j will be given by Equation (2),

$$g_\mathrm{j} = \frac{2\pi n_\mathrm{j} d_\mathrm{j}}{\lambda} \tag{2}$$

where d_j is the physical thickness and n_j the complex refractive index of the jth layer and, λ is the wavelength of the incident light.

The characteristic matrix M of all N layers of the multilayer thin film may then be represented by a total product of the characteristic matrices of each layer, as shown in Equation (3).

$$M = \left\{ \begin{matrix} m_{11} & i m_{12} \\ i m_{21} & m_{22} \end{matrix} \right\} = \prod_{\mathrm{j}=1}^{\mathrm{N}} M_\mathrm{j} \tag{3}$$

The transmittance of the multilayer is given by Equation (4),

$$T = \tau\tau^* \frac{n_\mathrm{s}}{n_0} \tag{4}$$

and τ is as shown in Equation (5),

$$\tau = \frac{2n_0}{(m_{11} + i m_{12} n_\mathrm{s}) n_0 + (i m_{21} + m_{22} n_\mathrm{s})} \tag{5}$$

where n_0 and n_s are the refractive indices of the medium and the substrate respectively.

From these theoretical equations it is possible to derive changes in transmittance in the layer being deposited. If all the layers that have already been deposited are represented by a single characteristic matrix and this matrix is used as a constant, the change in transmittance in the layer being deposited can be represented as a function of the physical thickness alone. If the rate of deposition and the refractive index within the layer being deposited are constant, the physical thickness will be directly proportional to the deposition time, so that the change in transmittance can be represented as a function of the deposition time. It then becomes possible, by non-linear fitting with the transmittance during deposition as a time function, to find the coefficient of the equation. Since the change in transmittance is a periodic function with respect to time, if the value within the sine function is designated as the phase, it becomes possible to determine the phase at the current time during deposition in real time, and by ending deposition upon reaching the phase at which it should be stopped according to the theoretical equations, high-accuracy optical thickness control can be achieved irrespective of the phase at which deposition should be stopped.

As was previously described, the use of thin film design based on thick layer and direct optical thickness monitoring system at the same time results in the appearance of multiple transmittance extremum in the wavelength of the monitor light, so that combining with phase-predictive optical thickness control makes it possible to obtain higher optical thickness accuracy.

Thin film deposition systems in which remaining layer thicknesses are reoptimized according to the deposition error as it takes place are in the process of becoming mainstream technology, but the layer in which error occurs and the amount of error varies with the batch being processed so that batch-to-batch reproducibility is comparatively poor. Furthermore layer thickness reoptimization requires highly accurate transmittance and other optical constants during deposition, so that when errors occur in estimating the optical constants reoptimization may be inaccurate. With phase-predictive optical thickness control, on the other hand, deposition proceeds accurately, under conditions in which errors are to a great extent prevented from occurring, so that in addition to having high accuracy, it has the further advantage of good reproducibility.

3. PROTOTYPES

3.1 Prototype Specifications and Deposition Method

A prototype gain-flattening filter was manufactured for use with an EDFA with a gain of 13 dB. Thin film design was based on an optical thickness of $3\lambda/4$, and 44 layers. Figure 4 shows the target loss profile and the design characteristic profile. With respect to the target loss profile the design characteristic flatness is 0.18 dB.

Optical thickness control was carried out by direct optical thickness monitoring using a halogen lamp as the light source. Monitoring wavelengths were chosen for each layer within the range of 1530 - 1562 nm, so that control was minimally affected by the monitoring wavelength. The timing of the end of deposition of each layer was effected by a phase-predictive optical thickness control, and a certain degree of timing compensation was applied so as to minimize error by considering shutter reaction time and so on.

Ion-assisted deposition (IAD) was the technique used for thin film deposition. Substrate temperature and the deposition conditions of the ion gun, etc. were optimized to produce the best possible thin film quality, and thin film deposition was carried out under conditions such that the deposition rate stabilized immediately after the start of deposition of each layer.

3.2 Appearance

Figure 5 shows the appearance of the prototype gain-flattening filter chip and the gain-flattening filter module using that chip. The chip measures 2.0 × 1.4 × 1.0 mm, and the module is 48 mm long by 6 mm in diameter.

3.3 Characteristic Test Results

Figure 6 shows the characteristic results obtained for the prototype. Flatness with respect to the target loss profile was 0.19 dB, and the insertion loss was 0.1 dB or less. At temperatures of from 25 to 70°C, the deviation of flatness was in the neighborhood of 0.01 dB.

3.4 Reliability Tests

As tests under various conditions of temperature and humidity, we subjected 10 chips to each of the tests shown in Table 2, which also shows the average values for minimum insertion loss deviation and wavelength shift before and after the tests. This demonstrates that there is no problem in terms of changes in characteristics and wavelength shift.

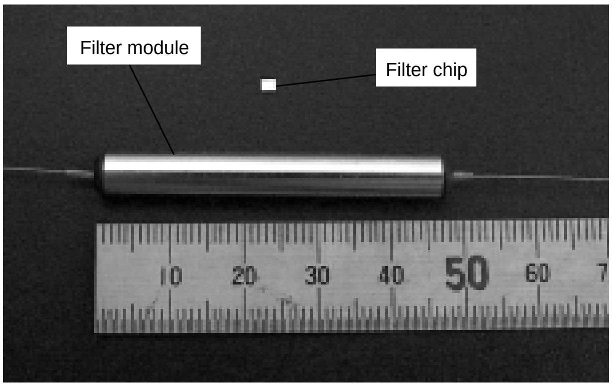


Figure 5 Appearance of prototype gain-flattening filter chip and gain-flattening filter module.

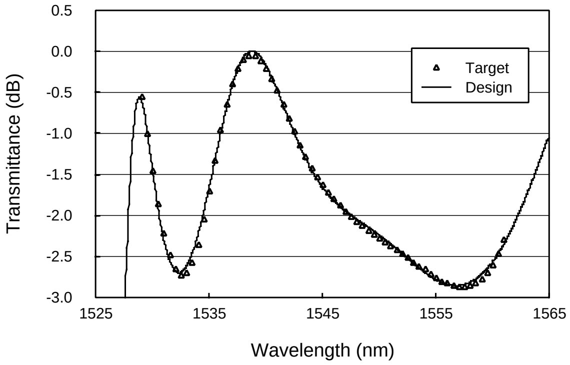


Figure 4 Designed characteristics of gain-flattening filter.

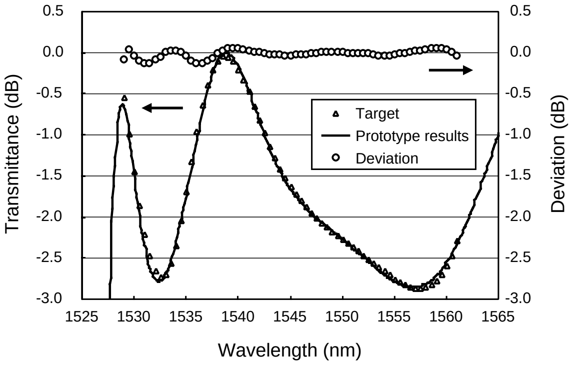


Figure 6 Results of characteristic test on prototype gain-flattening filter.

Table 2 Results of reliability tests.

Test item	Telcordia GR no. test conditions	Min. insertion loss deviation (dB)		Wavelength shift (nm)	
		Ave.	Std. Dev.	Ave.	Std. Dev.
High-temperature high-humidity aging	GR1209 85°C, 85%RH for 14 days	0.019	0.016	0.013	0.010
	GR1221 85°C, 85%RH for 2500 hrs	0.040	0.024	0.020	0.007
Temperature-humidity cycling	-40~85°C, 50 cycles	0.023	0.018	0.003	0.003
	GR1221 -40~85°C, 500 cycles	0.022	0.011	0.018	0.003
High-temperature storage	GR1221 85°C, <40%RH for 2500 hrs	0.085	0.009	0.024	0.012
Low-temperature storage	GR1221 -40°C for 2500 hrs	0.050	0.018	0.038	0.011
Boiling water immersion	Water at 100°C for 10 min	0.036	0.031	0.018	0.014

4. CONCLUSION

In the technology conventionally used for the optical thickness control of thin film deposition, it has proved difficult to produce dielectric multilayer thin film for gain-flattening filters, but in the current work it has been possible, using thin film design based on thick layer and adopting phase-predictive optical thickness control, to realize a gain-flattening filter for use in EDFAs with a gain of 13 dB that has a flatness of 0.19 dB with respect to the target loss profile.

Applications of gain-flattening filters made with dielectric multilayer thin film technology are not limited to EDFAs, but extend to Raman amplifiers and so on. Furthermore, the high-precision dielectric multilayer thin film deposition technology that has here been developed on the basis of thin film design based on thick layer and phase-predictive optical thickness control can, in addition to gain-flattening filters, be applied to edge filters, bandpass filters, and so on. There is an on-going trend in WDM communications toward wider signal bandwidths, and the technology developed here will make it possible to meet future demand for various types of filters.

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