Design Deposition and Characterization of Gain Flattening Filters

R. Blacker, D. Deakins,
I. Kameyama, A. Dummer,
D. Siegfried, and
C. Montcalm

Veeco Instruments Inc.
Fort Collins, Colorado
USA

B. Buchholtz
Buchholtz Engineering LLC
Windsor, Colorado
USA

Introduction

Recent advances in optical telecommunications technology have led to the development of dense wavelength division multiplexing (DWDM) filters, with designs based entirely on quarter wave layer thicknesses. DWDM filters, with band widths as low as 50 GHz (0.25 nm) are primarily used as 'signal monochromators' to separate individual transmission channels of the telecommunications spectrum. DWDM filters are used in arrays, each filter having a different center wavelength. The resulting 'device' covers a broader spectrum, up to 40 nm wide. In this broad spectrum, more than 100 separate DWDM filters may be in operation [1], yielding as many separate transmission channels, each theoretically carrying up to 40 Gbps of data.

Data transmission down each individual channel is subject to attenuation caused by inherent losses in the fiber that carries the signal. This limits current transmission distances to less than 600 km. Since transmission farther than 600 km is frequently necessary (e.g., sub Atlantic optical link), amplification of the signal is required. For this purpose, erbium doped optical fiber amplifiers are inserted into the transmission line at appropriate locations. As the signal passes each repeater station, the signal is amplified by up to 20 dB and passed on to the next stage.

Erbium doped fiber amplifiers (EDFA) are broad band devices, covering entire data transmission bands (S, C and L). Amplification is achieved by stimulating emission from the erbium ion. A typical amplifier may have up to 20 dB gain over the wave band, however this gain is not evenly distributed across the transmission band, being dependant up on erbium ion concentration, fiber length, emission cross section and the degree to which the fiber can confine the emitted radiation [2]. As a consequence of the uneven amplification, the signals from individual DWDM channels are amplified to different levels. This results in certain channels weakening with respect to others. When these signals are normalized, it is clear that some signals are 'weakened' with respect to others. Successive amplification of the data stream results in further reductions of these channels, their signals eventually becoming too weak to be effectively transmitted, resulting in loss of that data stream. An additional problem is that of increased cross talk (leakage) between adjacent channels, reducing the integrity of the transmitted data.

Current signal regeneration technology relies on optical to electrical conversion, with subsequent amplification, gain flattening of the electrical signal and conversion back to optical signal. This complex technique does not perform well at the 40 Gbps modulation frequencies being employed in data transfer, hence the need for all optical amplification. Unfortunately this technique provides a wavelength dependent gain, requiring the use of a gain flattening filter (GFF) to ensure that the amplification is leveled over the wave band. Current technology limits gain flattening levels to ±0.4 dB for various amplifiers [3,4].

This paper demonstrates the deposition of a GFF which is able to compensate for a gain range of 10 dB (i.e. a –10 dB GFF), and discusses the necessary considerations to allow a successful deposition.

Background to the Work

Gain flattening filters are highly complex filters that require stringent control over material properties, such as refractive index, as well as system properties, such as deposition rate.

The design of GFF, like most complex filters, requires that the deposition system is taken into consideration and that its capabilities are balanced with the need to allow reasonable design convergence to the target. For the current work (design of a –10dB filter covering the C band: 1525 nm to 1565 nm), several options were considered, each having merits and demerits in terms of design ease and system compatibility.

The initial consideration is for the filter shape itself. As discussed above, the shape of an EDFA is relatively arbitrary; so to ensure that the filter being produced is representative of such filters, it was decided to try to compensate for an erbium doped amplified stimulated emission (ASE) signal. Erbium ASE are readily available sources that mimic the EDFA. This source uses a pumped erbium doped fiber to produce the signal output illustrated in Fig. 1.

As can be seen, the signal output has severe wavelength dependencies, displaying peak emission at 1532 nm, and minimum emission at 1538 nm. This rapid excursion of 4 dB emission over a 6 nm span creates some difficulty for the filter design. This region is considered to be the most difficult to both fit a practical filter design to and to ensure good thickness tolerances during deposition. In addition, it is clear that the definition of error tolerance (discrepancy between target and filter spectra) plays a key role in estimating filter performance. In our definition, the discrepancy between measured filter performance and target performance should remain within ±0.3 dB. In regions where the filter has a larger derivative function (i.e., steeper slopes) it is more critical to maintain the filter shape close to the target – minor wavelength errors result in disproportionately large error functions.

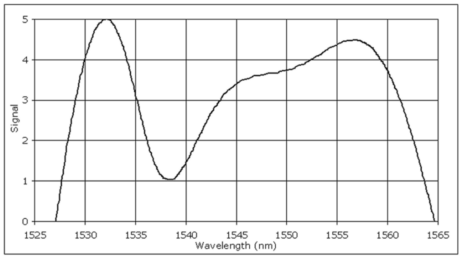

Figure 1 Output of the ASE Source

Having noted that the filter shape is critical in the areas mentioned above, one faces several choices for design methodology, including (not exhaustively); designs based on quarterwave filter design principles; designs where layer thicknesses are not restricted to either being quarterwave or non-quarterwave or any limited thickness, and finally, designs where the layer thicknesses are restricted to levels where an optical monitoring system can usefully be operated. This paper considers the use of non-quarterwave designs only.

Process Considerations

The GFF filters demonstrated in this paper were deposited using a developmental dual ion beam sputter deposition (DIBSD) tool. The layer materials are silica and tantala;

the silica being sputtered from an oxide target and the tantala from a metal target.

The typical operating conditions for the DIBSD system provide a stable operating platform, its inherent rate stability ensures that layer thicknesses will typically be deposited with better than a 1% thickness accuracy when the system is controlled by time and constant power (i.e. time – power mode). In this way it is possible to deposit simple filters using predetermined times for each layer with no manual intervention. With the addition of quartz crystal monitoring this estimation routine is marginally improved for very long depositions. For more complex filters it is required to use an optical monitoring system that allows layer thicknesses (optical) to be determined to better than 0.1% accuracy.

To overcome this variation, the deposition system was modified with a heater control package using dual loop PID control over a thick film heater panel placed parallel to the rear face of the substrate at a distance of 3 mm [5]. In this way the different operating conditions for each layer material are compensated, the substrate temperature being maintained to better than 1° C.

Under normal operation the substrate is subjected to varying heat loads as a result of the different operating conditions required to deposit each layer material. In our deposition tool, normal conditions allow silica deposition to equilibrate at 105° C, whilst tantala deposition equilibrates at 150° C. Since it takes several hours for the temperature to equilibrate, the deposition is typically done under non-equilibrium since layer deposition times are less than the settling time. This varying heat load has a follow on effect of changing the deposition rates of layer materials in a non-linear manner.

The standard ion beam deposition conditions are given in Table 1.

Table 1: Deposition Parameters

Parameter	Deposition Beam	Assist Beam	
	Both Layers	Silica Layer	Tantala Layer
Beam Voltage	1250V	400V	550V
Beam Current	600mA	75mA	150mA
Accel Voltage	250V	600V	250V

In addition to the beam conditions, the chamber is operated at a pressure of 1x10^{-3} mbar, with 25 sccm oxygen introduced into the chamber, and an additional 12 sccm oxygen flowing through the assist beam. Argon is used as the carrier gas with a total flow rate of 21 sccm.

◆

Design of the GFF

Determination of Material Refractive Index

GFF is considered a broad band filter, covering the entire C band of transmission (in the present case) which lies between 1525 and 1565nm. It is necessary to carefully determine the material indices across this band to allow appropriate filter designs to be realized.

Deposition of single layers of silica and tantala was carried out to enable determination of the refractive indices using a variable angle spectroscopic ellipsometry (Woolam VASE 2000MI). The single layers of 20 quarter wave optical thicknesses (QWOT) (1550 nm) were deposited on to <100>-silicon wafers. The indices are illustrated in Table 2. As can be seen, the dispersion of index over the waveband of interest (1525 to 1575 nm) is 0.0002 for silica, and 0.0007 for tantala. Though this level of dispersion over the C band seems low, the GFF design does need to account for it. Fig. 2a illustrates the effect of not accounting for this level of dispersion.

Table 2 Optical Index of Materials

Wavelength (nm)	Silica Index	Tantala Index
1500	1.4723	2.0808
1510	1.4723	2.0807
1520	1.4722	2.0806
1530	1.4722	2.0804
1540	1.4721	2.0803
1550	1.4721	2.0801
1560	1.4721	2.0800
1570	1.4720	2.0799
1580	1.4720	2.0798
1590	1.4719	2.0796
1600	1.4719	2.0795

The discrepancy between the two designs appears to be minimal; however when the error (difference between the target and design curves) is extracted as shown in Fig. 2b, the difference becomes clear. The design with no dispersion fails to meet the ±0.3dB tolerance specification, whilst the addition of the extremely small level of dispersion yields a result that fulfills the specification.

The following illustration displays the extreme sensitivity of GFF designs to any process errors such as a changing or poorly known refractive index. A similarly disproportionate response is observed with relatively small thickness errors: a random error of greater than 0.1% results in a filter shape that falls far outside the error tolerance specification. In order to maintain this extreme level of optical thickness tolerance, it is necessary to utilize an optical monitoring system during deposition of the filter.

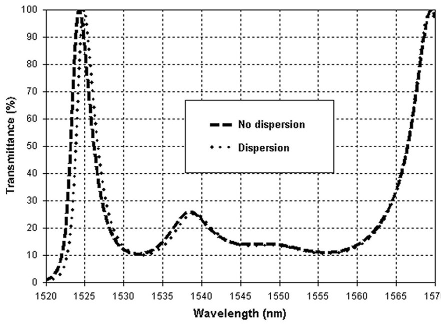

Figure 2a Effect of Dispersion on GFF Design

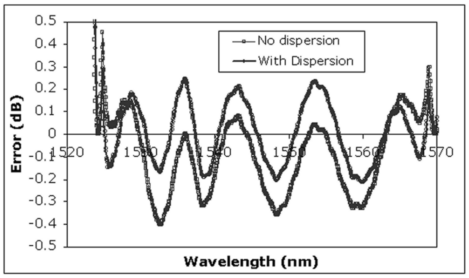

Figure 2b Dispersion Induced

Non-Quarterwave GFF Design

Gain flattening filter designs typically utilize non-quarterwave rather than quarterwave layers. This generally provides reasonable scope for enabling rapid design convergence for even quite complex filters. Within the non-quarterwave design principle there are two main techniques. The first method allows each layer thickness to vary between some reasonable preset limits (between 0.25 QWOT and 10 QWOT for example). The second technique is to impose layer thickness restrictions to allow for improved layer end-point determination when optical monitoring is used during filter manufacture.

GFF Design Using Unrestricted Layer Thicknesses

An example of a GFF design using largely unrestricted layer thicknesses is illustrated in Fig. 3. The design has the minor limitation that each layer thickness is required to be >0.25 QWOT (at 1550nm).

The design of the GFF filter is carried out using both Optilayer and Essential MacLeod thin film software packages. An initial starting point for the design consisting of 97 layers is derived manually from a simple mismatched mirror stack. This simple design provides a reasonable starting point for the automatic optimization of the GFF. Using the relaxed layer thickness specifications the design rapidly converges to a shape that lies within the ±0.3dB specification for the filter. During the optimization, however, some layer thicknesses are reduced to below the minimum thickness of 0.25 QWOT. By manual intervention these layers are thickened by adding a half wave thickness to the layer. Further automatic optimization re-establishes the required GFF shape. It is noted that the number of layers can be increased or reduced during the optimization routine, and in this case the final number is 89 layers. This design is illustrated in Fig. 3.

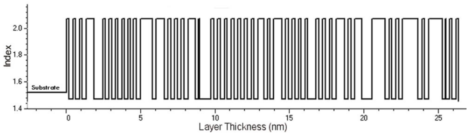

Figure 3 Unrestricted Layer Thickness Design for GFF

Using the above example of GFF design it is possible to rapidly produce a 'good' theoretical design, however, in practice this design may be difficult to manufacture. Brief consideration of the accuracy required for each layer thickness reveals that the design falls outside the required ±0.3dB specification when a random layer thickness error is implemented.

GFF Design Using Restricted Layer Thicknesses

The previous example provided easy and rapid convergence of the filter design to the target curve, however such a design would prove difficult to manufacture successfully without 'perfect' control over the deposition.

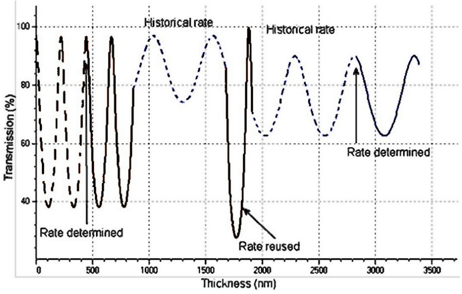

Figure 4 Optical Monitoring Calibration Scheme

One of the benefits of optical monitoring is that layer thickness can be determined in real time during the deposition of the layer. Hence the termination point of a particular layer may be more accurately determined. The system employed in this work provides an updated estimate of optical deposition rate at each fringe turning point, but only after a full wave of layer deposition. To allow layers that are less that the 4 QWOT minimum thickness to be successfully deposited, an initial deposition rate (determined by prior calibration) is programmed into the system. This rate is updated with each successive fringe turning point after the fourth turning point of each layer. Ideally therefore the individual layer thicknesses should be greater than 4 QWOT thick, or at least provide four or more turning points during transmission monitoring. This methodology is illustrated in figure 4. As can be seen, the initial rate is updated for layer #1 at the fourth turning point, however layer #2 does not provide sufficient turning points to allow this to happen. Layer #3 initially relies on the final rate of layer #1, and is updated after the fourth turning point, whilst layer #4 still relies on the historical rate input before the commencement of the layer deposition.

Using the above scheme the deposition rate is updated as close to the actual end point of each layer as possible, rather than the layer time being determined at the start of the layer only. This rate-updating technique allows in layer rate variations to be compensated for, increasing layer thickness accuracy from the 1% possible using time-power deposition to better than 0.1%. The expense of this technique is in increasing total filter thickness (hence deposition time), and so an upper thickness limit of 60µm is placed on the filter design. This threshold is derived from total deposition time providing a viable process.

Using these design principles, convergence of a filter that meets the ±0.3dB specification is considerably more difficult than for the previous example. It is necessary to manually intervene during the optimization routine to increase thinner (sub full wave) layers, and decrease very thick layers to maintain the filter to less than 60µm total thickness.

An example of a completed GFF design is shown in Fig. 5. As can be seen, the filter has a total thickness of 55µm and consists of 39 layers, each with an average thickness of greater than 6 QWOT, the thinnest layer being 4.2 QWOT.

Error tolerance analysis of this filter design reveals that a random error of 0.1% layer thickness moves the design beyond the boundaries of the tolerance specification. To overcome this severe constraint it is necessary to further increase the stability of the system by implementing the thermal control system. With no thermal control of substrate temperature, the deposition rate is seen to increase through the layer by up to 1% for tantala. An equivalent decrease is noted for silica layers. This changing rate is as a result of the systematic thermal variations discussed above.

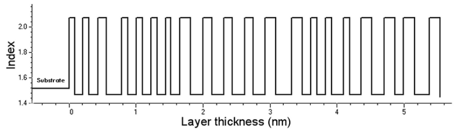

Figure 5 Index Profile of 37 Layer G

With the layer deposition temperature controlled to within 1° C, the in layer rate variation reduces to 0.3% (for tantala). This three times increase in rate stability further improves the accuracy of the layer end point determination scheme, and allows the overall stability to be improved to a level where successful GFF deposition can be achieved.

Deposition and Characterization of GFF Filter

Using the filter design illustrated above, the GFF filter was deposited on to Ohara WMS-13 substrate material. To reduce the presence of substrate interference difficulties, the substrate was anti-reflection coated prior to filter deposition.

Deposition of the 55µm thick, 39 layer filter was carried out using optical monitoring at 1550 nm wavelength.

The filter shape is illustrated in Fig. 6, along with the error determined as the deviation of filter shape from the desired target shape. As can be seen, the filter shape closely matches the target shape, with a deviation of less than 0.3dB for the majority of the filter. The deviation exceeds this tolerance only at the lower range of bandwidth.

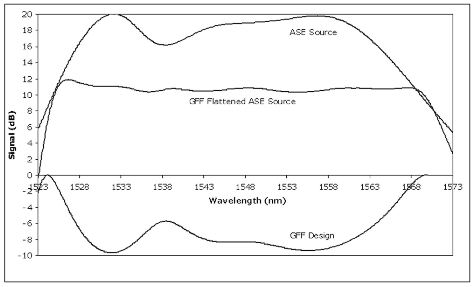

Figure 6 Spectral Shape and Error of Deposited GFF

Conclusion

The GFF is a complex filter with an arbitrary shape determined by the amplification response of the EDFA that the filter is intended to compensate for. The degree of difficulty of depositing the GFF is determined by several factors, most prominently depth of the filter and the error tolerance placed on the filter. A -10 dB filter with ±0.3 dB tolerance was discussed.

Deposition of the –10 dB GFF was accomplished by consideration of the deposition system characteristics, and of the material systems being utilized. Prior knowledge of the layer materials, their refractive indices and optical dispersion was critical to success. It was shown that extremely low levels of optical dispersion are sufficient to cause the filter shape to deviate from the target. Levels of dispersion of the order 0.0002 for the low index (silica) material, and 0.0007 for the high index (tantala) were found to be significant in distorting the filter shape.

In addition to the requirement for a well known refractive index, it is necessary to employ layer thickness monitoring to achieve the required layer accuracies. It was shown that thickness errors of greater than 0.1% will yield a filter shape that does not meet the tolerance specifications.

Successful design of the GFF has been demonstrated using two non-quarterwave design principles, with one being shown to provide ease of design, but poor manufacturability, whilst the other demonstrates the reverse.

Deposition of the manufacturable GFF required good system stability in terms of deposition rate. This stability was achieved by use of a thermal control package that controlled substrate temperature to better than 1° C. The rate stability was improved by a factor of three. The use of an optical monitoring system was still necessary to enable the required layer thickness accuracy to be achieved.

References

1. C. Barnard, J. Klein and V. Tzlov, “Modeling Optimizes EDFA Design,” *WDM Solutions*, 33, June 2000.
2. C. Barnard, T. Mirtchev and K. Klein, “Scientific and computational challenges in the simulation of broadband fiber amplifiers,” *Optical Networks Magazine*, 63, September 2001.
3. S. Li, K. S. Chiang, and W. A. Gambling, “Gain flattening of an erbium-doped fiber amplifier using a high-birefringence fiber loop mirror,” *IEEE Photon. Technol. Lett.*, 13, 942, 2001.
4. M. Janos, B. Smith and S. Poole, “Arbitrary-response gain flattening filters with low amplitude and phase noise and built in ASE suppression,” SPIE Vol 3896, 380, 1999.
5. D. Deakins, I. Kameyama, B. Buchholtz, and R. Blacker. “Temperature control of glass substrates in ion-beam-assisted sputtering deposition system.” SVC 45th Annual Tech. Conf. Proc. (2002).

Veeco Instruments Inc.
2330 E. Prospect
Fort Collins, CO 80525
Find out more at www.veeco.com
or call us at 1.970.221.1807