Recent Advances in Thin Film Interference Filters for Telecommunications

N.A. O'Brien, M.J. Cumbo, K.D. Hendrix, R.B. Sargent, and M.K. Tilsch,
JDS Uniphase, Santa Rosa, CA

Key Words: WDM; Thin film interference filter; Narrow bandpass filter; Wide bandpass filter

ABSTRACT

Explosive growth in the use of the Internet in recent years has driven a corresponding growth in the fiberoptic telecommunications infrastructure that enables it. Wavelength division multiplexing (WDM) is a technology that increases the bandwidth of this infrastructure by utilizing multiple wavelengths on each optical fiber in a cable. WDM is currently used in practical systems to increase the capacity of each fiber by 10 to 100 times over single-wavelength approaches. Thin film interference filters have played an important role in the deployment of WDM systems. Types of interference filters which are currently employed in WDM systems include narrow bandpass filters for multiplexing and demultiplexing; a common example is to combine or separate channels spaced 100 GHz (0.8 nm) apart. Other types of interference filters employed include wide bandpass filters for combining optical pump and signal light in an erbium-doped fiberoptic amplifier (EDFA), and filters which equalize the gain at different wavelengths in an EDFA.

In this paper we review requirements placed on thin film interference filters by WDM applications. Key aspects of film properties and deposition process attributes will be presented. The technology continues to evolve, and recent advances will be described which have led to the production of filters that are capable of separating wavelengths spaced as closely as 50 GHz.

1. INTRODUCTION

The wide proliferation of the Internet in the mid 1990s has led to an exponential growth in bandwidth demand. Traditional communication systems such as time division multiplexing (TDM), where multiple signals of one wavelength are transmitted through a single fiber but are distinguished from each other by specific time intervals, were not economically viable even at 10 Gbit/sec. WDM emerged as the new technology that increases the capacity of existing fiber by sending multiple (multiplexing) wavelengths down one fiber. Each wavelength can have different bit rates and varying types of traffic such as data, video, or voice. The total bandwidth per fiber is the sum of the bit rate of each wavelength. Systems have been built with 40, 80, and 128 wavelengths per fiber. Early systems started out with 2 and 4 channels.

WDM has been enabled by several technologies [1]. One key technology is the optical amplifier, specifically erbium-doped fiber amplifier (EDFA) that is able to amplify several wavelengths simultaneously and optically over 1525 to 1565 nm (C-band) and 1570 to 1610 nm (L-band). EDFAs have replaced expensive and bulky electrical domain regenerators, and enabled longer distance transmission without amplification, i.e., 120 km between EDFAs compared to 50 to 80 km with regenerators. The EDFA has defined the usable telecom wavelength ranges as the C and L-band. Recent advances in fiber technology have extended the optical communications spectrum from 1300 nm to the L-band, opening up more opportunities for bandwidth capacity increase.

Figure 1 is a simplified illustration of a point-to-point WDM system with some of its key elements, a multiplexer, optical fiber, optical amplifiers, optical add/drop module (OADM), switch, and a demultiplexer. A multiplexer combines a number of distinct wavelengths into a single fiber. A demultiplexer works in the reverse manner. It separates a stream of wavelengths into their individual channels. OADMs are used to drop a specific wavelength from a stream of others and reinsert another signal at the same wavelength. They are used to drop/add channels at smaller sites as in metropolitan locations.

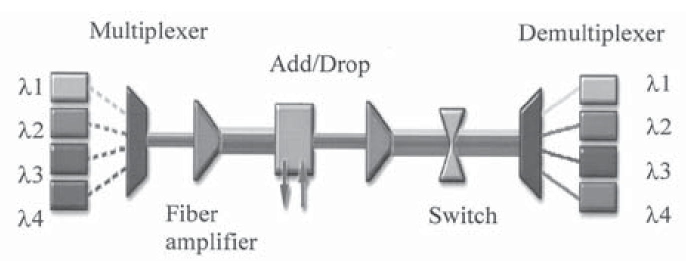

Figure 1: An illustration of the key components present in a point-to-point WDM system.

The emphasis of this paper will be on filters used in multiplexers (mux) and demultiplexers (demux). Technologies and principles that apply to mux/demux type filters apply also to others that will not be discussed in this paper, such as gain equalization filters [2] pump combiners, and wavelockers [3]. The paper will be organized as follows. In section 2, we will start with a review of the various technologies used for WDM.

44th Annual Technical Conference Proceedings—Philadelphia, April 21–26, 2001 ISSN 0737-5921

In section 3 we will show typical filter performance requirements for narrow bandpass and wide bandpass filters. We will review the building blocks of thin film interference filters in section 4, followed by results and recent advances in section 5. Future trends in thin film interference filters for the Telecom market will be discussed in section 6. We will end with conclusions in section 7.

2. FILTER TECHNOLOGIES

There are several competing technologies that are used for multiplexing and demultiplexing. We will touch on the key ones here with a brief evaluation of their pros and cons.

2.1 Thin Film Interference Filters

One common way to employ thin film filters in WDM devices is shown in Figure 2. The device shown in the figure is a demultiplexer.

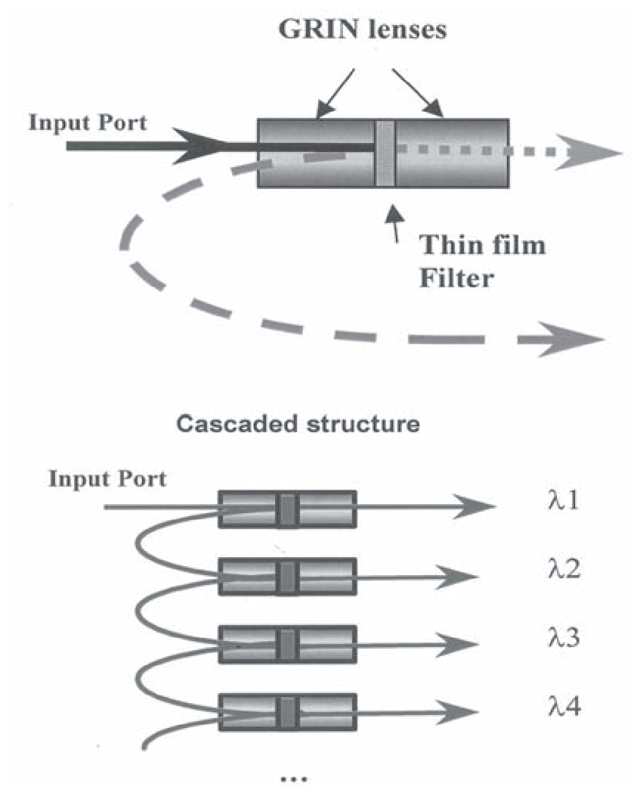

Figure 2: a) A three-port coupler using a thin film interference filter. b) A cascaded structure of thin film couplers used in a demultiplexer (as shown) or a multiplexer.

In this approach, a filter is sandwiched between two gradient-index (GRIN) lenses. Light from an input fiber is collimated by the first lens and is incident on a thin film filter; the filter transmits a specific wavelength and reflects others. The second GRIN lens focuses the transmitted light onto an output fiber, while the first lens (working in reverse) focuses the reflected light onto another output fiber. Typically the dimensions of the filters and lenses in these devices are on the order of a few millimeters.

These devices have three fiber ports, and are sometimes referred to as "three port couplers." A multiple wavelength demultiplexer can be constructed by connecting a series of three port couplers in a cascade to separate the desired channels. The same basic device may also be employed as a multiplexer by using it in reverse.

Optical thin film interference filters have found widespread use in the fiberoptic telecommunications industry as a result of several key advantages. The filters and the devices built from them are thermally stable, exhibit excellent spectral performance, have low polarization dependence, and can be readily produced in high volumes. Inherent to the cascading architecture described above is an increase in optical power loss (insertion loss) as channel count increases due to cumulative coupling losses from one coupler to the next.

2.2 Fiber Bragg Grating (FBG)

A periodic variation in the refractive index of the core of the fiber over the length of a fiber forms a FBG. The index variation, which is on the order of 10^{-3} to 10^{-4}, is achieved by exposing the fiber to intense UV light so that the photosensitivity in the germanium-doped silica core induces a permanent index change [4]. The periodicity pattern is achieved by use of phase masks to create the desired interference pattern. Each period is in the range of 0.5 to 10 microns in length. The FBG reflects only the wavelengths of incident light that satisfy Bragg's relation of $\lambda_B = 2$ x (index of refraction) x period. All other wavelengths are transmitted. Narrower bandwidths require longer gratings. The length of FBG filters is on the order of a few centimeters.

FBGs are easily coupled into the fiber hence minimizing insertion loss. They are also compact devices due to their fiber-based structure. However, since the reflected wave travels back into the same fiber as the incident wave, a circulator is needed to drop the reflected signal. This adds to the cost of a FBG device. They are also sensitive to temperature, which requires the use of active temperature control of the device as part of the FBG package, although athermal packaging has also been used. FBGs are manufactured individually with a cycle time of 2 to 5 minutes per filter for the writing of the grating itself.

2.3 Arrayed Waveguide Grating (AWG)

AWGs are silica-on-silicon devices that are patterned into SiO_2 using commercial photolithography techniques commonly used in the semiconductor industry. Light from an input fiber is distributed to an array of waveguides through a first coupler. Light in each waveguide will travel a different distance so that at the output each wavelength will have a different phase. Due to a wavelength-dependent tilt, the light is separated into individual wavelengths [5]. Another coupler refocuses each wavelength to a separate individual fiber.

One of the key advantages of AWG technology is the compactness of the device. DWDM modules are available in 40 channels—100GHz spacing all on one “chip.” Cost per channel is rather low for AWG in comparison to other technologies. There has been quite a bit of discussion around optical integration of AWGs with other device functions such as photodetectors, for example. Relatively low insertion loss is another inherent benefit primarily for high channel count devices. However, coupling AWGs to input and output fibers is not very straightforward and a major source of loss, making them unattractive for low channel count devices. Additionally, the flatness of the individual channels is poor due to the guassian profile of the insertion loss of device. AWG are fabricated on standard semiconductor size Si wafers. Each wafer can produce 10 to 20 AWG filters. Depending on the channel count, a single filter will range in size from 3 to 8 cm long. The manufacturing tolerances for AWGs are extremely tight. The index uniformity of the deposited waveguide has to be better than 10^{-5}. AWG can suffer from high polarization dependent loss (PDL) due to stress-induced birefringence. AWGs require active temperature control to maintain constant device performance.

2.4 Other

Another all fiber-based mux/demux technology is based on fused fibers that are arranged to form a Mach-Zehnder interferometer structure. These devices are known as fused biconically tapered (FBT) couplers [6]. An emerging integrated grating technology, other than AWG, is the etched echelle grating on InP wafers [7].

3. THIN FILM FILTER PRODUCT REQUIREMENTS

3.1 Narrow Bandpass Filters

In dense WDM (DWDM) systems, wavelengths are tightly spaced apart with as low as 200 GHz, 100 GHz, or 50 GHz of channel spacing (i.e., 1.6 nm, 0.8 nm, and 0.4 nm at 1550 nm). The channels are placed on the International Telecommunications Union (ITU) frequency grid. The demultiplexer separates the various channels individually with minimal loss of signal power of each channel and low cross talk between channels. An industry standard document, Telcordia Generic Reliability 1221, details a number of tests that filters have to undergo [8]. One example is a high temperature damp heat test, where the filter is placed at 85°C/85% relative humidity for 2000 hours. Table 1 contains typical specification values for a 200 GHz, 100 GHz, and 50 GHz filters. These filters are generally referred to as ITU filters. The –0.5 dB relative bandwidth (RBW) is the passband bandwidth at –0.5 dB (89%) relative to the peak center wavelength. The –25 dB RBW is the stop band bandwidth at –25 dB (0.3%). For a similar shape factor (stopband badwidth/passband bandwidth), the shift in center wavelength of the filter with temperature is required to be ≤ 2 pm/°C for 200 GHz filter, ≤ 1 pm/°C for 100 GHz, and ≤ 0.5 pm/°C for 50 GHz, over the 0 to 70°C operating temperature range.

Table 1: Typical ITU filter requirements.

	200 GHz	**100 GHz**	**50 GHz**
-0.5 dB RBW	> 0.70 nm	> 0.40 nm	> 0.25 nm
-25 dB RBW	< 2.40 nm	< 1.20 nm	< 0.60 nm
Insertion loss	< 0.8 dB	< 0.8 dB	< 1.0 dB
PDL	< 0.05 dB	< 0.05 dB	< 0.05 dB

3.2 Wide Bandpass Filters

Some mux or demux systems are designed such that multiple ITU channels are dropped (or added) simultaneously. One of the main benefits of these filters is the reduced loss obtained with these devices in comparison with cascaded ITU filters. An example of a multiple channel filter is 4-skip-1 filter for 100 GHz channels. This filter transmits four channels of 100 GHz filters. By skipping a single 100 GHz channel, the stopband is allowed to extend into an adjacent 100GHz channel on both sides of the filter. However, the demand for greater bandwidth makes skipping channels undesirable. This has driven filter requirements to be more challenging, such as 4-skip-0 with 100 GHz spacing which makes the filter shape factor closer to 1 and much harder to design and build. This trend toward steeper filter slopes includes the wider S- (1360 nm to 1480 nm), C-, and L-band splitters.

Table 2: Examples of some wide bandpass filter requirements.

	4-skip-1 100 GHz	**4-skip-0 100 GHz**	**C-band Splitter**
-0.5 dB RBW	> 2.9 nm	> 2.9 nm	> 37 nm
-25 dB RBW	< 5.1 nm	< 3.5 nm	< 45 nm
Shape factor	1.8	1.2	1.2
Insertion loss	< 1.0 dB	< 1.0 dB	< 1.0 dB
PDL	< 0.05 dB	< 0.05 dB	< 0.05 dB

Along with the trend toward steeper filters is a trend toward filters with lower passband ripple. Where once 0.3 or 0.4 dB of passband ripple would suffice, now the desire is to have filters with passband ripple of less than 0.15 dB. This also makes the filter design and manufacture more difficult.

4. BUILDING BLOCKS FOR THIN FILM INTERFERENCE FILTERS

There are four main ingredients to successfully produce WDM thin film interference filters. First, one has to start with a good thin film design that meets or exceeds the requirements. Second, one has to choose a substrate material that enables the required small shift in center wavelength with temperature. Third, the thin film deposition process has to a) produce high quality films and b) be stable over an extended period of time. Fourth, an optimum optical thickness monitoring technique is necessary to provide the high precision control required in producing these filters.

4.1 Thin Film Design

Thin film interference filters consist of alternating layers of high and low refractive index materials deposited on a glass substrate. ITU and wide bandpass filters are designed with multiple cavity Fabry-Perot structures [9]. A single cavity dielectric Fabry-Perot filter consists of two high reflectors composed of alternating quarter waves (QW) of high (H) and low index (L) materials and separated from each other by a halfwave stack of high or low index often referred to a spacer. In designing the types of filters described in the previous section, a thin film designer may adjust several parameters to obtain the desired filter function that meets a given set of specifications. Increasing the number of cavities generally makes the filter steeper (i.e., shape factor closer to one) and wider. Increasing the spacer thickness makes the filter narrower. Adding more HL pairs to the reflector stacks results in a better rejection or isolation, i.e., lower transmittance in the rejection band, and in a narrower filter.

An ITU filter design may consist of 3 to 5 Fabry-Perot cavities. The total thickness range may vary from 20 to 50 microns. A wide bandpass filter design may consist of up to 10 or even 20 cavities.

4.2 Film and Substrate Properties

The filter requirements discussed earlier in section 4 along with the types of filter designs described in the previous section impart a set of stringent requirements on the film properties themselves. The films have to be dense with amorphous or a nanocrystalline structures. They should have very low absorption ($k < 10^{-6}$) and scatter. In order to meet the requirement of low thermal shift, dL/dT, of 0 to 2 pm/°C, glass substrates of high coefficient of thermal expansion are used [10]. A glass type with a coefficient of thermal expansion in the range of 70 to 120 x 10^{-7}/°C stretches the thin film laterally causing an optical thickness reduction that compensates for the optical thickness increase that usually occurs in thin films as a function of temperature.

A thermal shift of 0.2 pm/°C has been achieved with the proper choice of glass substrate as shown in Figure 3 for a 50 GHz filter.

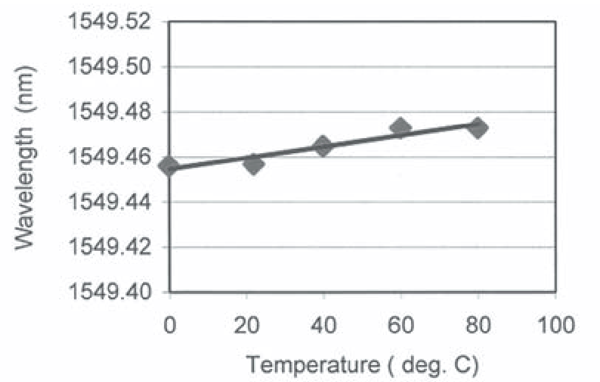

Figure 3: Thermal shift of a 50 GHz filter shown to be about 0.2 pm/°C.

4.3 Thin Film Deposition Processes

To date, physical vapor deposition (PVD) processes are used in the production of WDM filters. More specifically, it is energetic PVD processes that are preferred which are necessary to obtain the desired film properties of high thermal, moisture, and environmental durability. The three most commonly used processes are plasma ion-assisted deposition (IAD) [11–13], ion beam sputtering [14, 15], and ion-assisted reactive sputtering [16, 17].

IAD is an evaporation process that uses electron beam guns for the low index e.g., SiO_2, and high index materials, e.g., Ta_2O_5. Oxygen and/or argon ions are used in the plasma ion source to bombard the substrate and provide the necessary densification of the growing film. The ion source provides ion current densities in the range of 0.5 to 1 mA/cm^2 at the substrate, with ion energies up to 200 eV. Relatively fast deposition rates are obtained with this process. A three-cavity 100 GHz filter can be produced in 12 hours. A key drawback of an evaporation process is the random spatial distribution of the evaporant plume over a long period of time. However, there has been a recent report indicating the use of feedback controlled-electron beam guns along with a quartz crystal monitoring system that monitors the distribution and compensate for the spatial variation by adjusting the e-gun operation parameters [13].

Ion beam sputtering (IBS) uses a Kaufman type gridded ion source to sputter metal or oxide targets with 1000 to 1500 eV ions. A percentage of these ions, typically Ar^+, is converted into reflected energetic neutrals which can be buried in the growing film, and which can produce relatively high compressive stresses in the films. However, IBS is known to produce films with very low loss and the process is usually known to be very stable over a long period of time. Deposition times are rather long with IBS. A 24 to 40 hour long run is not atypical for a 3-4 cavity 100 GHz filter. Machine builders have considered installing a load-lock system on their IBS machines to further improve process stability and reduce ‘run’ time [15].

Microplasma® process is an example of a low pressure DC magnetron sputtering process where metal targets are sputtered with argon gas. Oxygen ions from an ion source are used to bombard the substrate during film growth. The substrate and targets are placed at a throw distance of 16” to provide the desired coating uniformity on a rotating substrate. In order to avoid thermalization of the sputtered particles at such large throw distance low working pressures are used in the range of 5×10^{-5} to 1.5×10^{-4} torr. This process is claimed to have IBS-like film properties but with faster deposition rates than IBS.

Most of these processes use single rotation substrate holders. Substrates as large as 300 mm in diameter have been used [14]. Wavelength uniformity has been reported to be less than 0.2% across 100 mm radius [13]. However, in order to produce filters at acceptable areal yields, the center wavelength (CWL) radial uniformity for an ITU filter product, e.g., 200 GHz, has to be less than its channel spacing of 1.6 nm. This translates to a uniformity requirement of < 0.1% for 200 GHz and < 0.05% for 100 GHz when producing filters in the C-band. We have achieved a CWL uniformity of less than 0.05% with excellent filter shape on an area of sufficient size that yields thousands of good filters per run.

4.4 Thickness Monitoring System

The deposition of telecommunication filters requires very tight tolerances on thickness control. Figure 4 shows the transmission spectrum of a 100 GHz filter. The solid line describes the performance as designed. The dotted line shows the performance where the thicknesses of all layers are randomly disturbed by 0.5%. This would be the expectation if the filter was monitored by quartz crystal monitoring or some other indirect method. The filter is completely deteriorated and would be of no use for a 100 GHz WDM system. For that reason composite turning point monitoring at the center wavelength is typically employed. This technique has the advantage of inherent error compensation. A cutpoint error in one layer is automatically compensated by the next layer with very little distortion to the filter shape [18, 19]. The dashed curve in Figure 4 shows a simulation for 1% thickness accuracy on each individual cutpoint. The final filter performance is almost indistinguishable from the design performance (solid line).

Two fundamental options exist for the hardware of a center wavelength monitoring system: a laser system or a white light source coupled with a monochromator. The laser has an exceptionally high spectral irradiance at the desired wavelength. However, the amplitude and frequency stability over a long period of time is critical. Furthermore, lasers have a limited range of tunability. A white light system may be inherently more stable, can easily cover a wide spectral range but may give higher signal to noise problems specifically for very narrow bandpass filters. Both types of systems are successfully used in the industry.

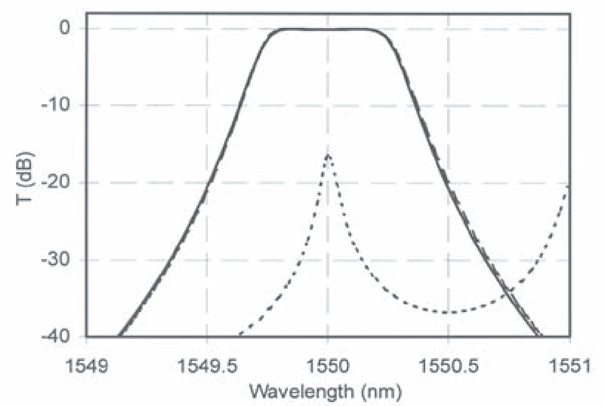

Figure 4: Transmission spectra of a 100 GHz filter; filter as designed (solid curve); filter with 0.5% random thickness error on each layer, representing non-composite monitoring (dotted curve, lower curve); filter with 1% thickness error for turning point monitoring at the center wavelength (dashed curve, almost indistinguishable from design spectrum).

5. RECENT FILTER RESULTS

We have produced 50 GHz filters with an insertion loss of better than –0.4 dB and excellent spectral performance. An example of a 50 GHz filter is shown in Figure 5. We have produced various types of wide bandpass filters similar to the ones described earlier. In Figure 6, we show an example of an 4-skip-1 100 GHz filter.

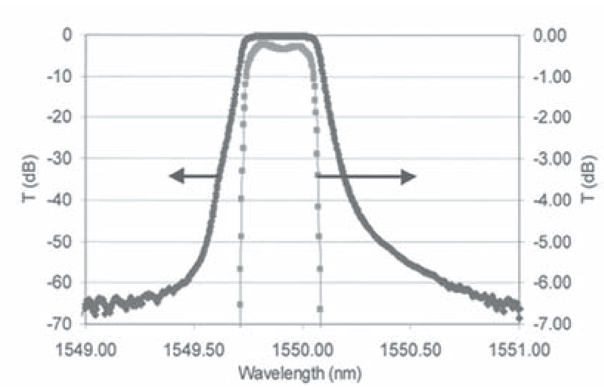

Figure 5: A transmission spectrum of a typical 50 GHz thin film filter.

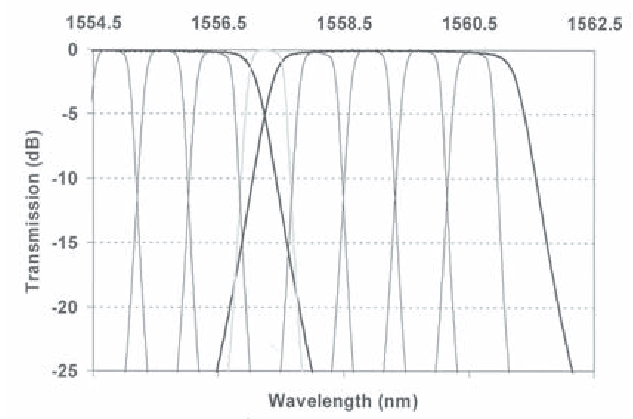

Figure 6: A transmission spectrum of a 4-skip-1 filter on a 100 GHz grid. The black plots represent the passed 100 GHz channels while the grey plot is the skipped one.

6. FUTURE TRENDS

Future filter demand is expected to arise from the metropolitan telecom market as opposed to the long haul and submarine markets that have dominated much of the growth over the last 5 years. There has been a lot of talk recently about coarse WDM (CWDM) for the metro market [20]. Coarse refers to larger channel spacing *and* width in comparison to DWDM. Channel widths have been specified at 13 nm wide and spacings of 20 nm centers on wavelengths ranging from 1300 to 1620 nm.

The demand for filters is expected to remain strong. However, the current WDM components and networks costs are too high for the metro market whose demand for bandwidth and reach is lower than the long haul market. Many technologies are being developed to enable overall lower cost systems. For thin film interference filters to remain competitive, the price per filter must continue to be reduced. Hence, increasing throughput and yields will be the focus of filter manufacturers over the next few years.

7. CONCLUSIONS

Thin film interference filter is a mature technology that has been proven to exhibit good optical performance and reliability for the telecom industry. Furthermore, the technology is highly flexible and suitable for a wide range of applications. The same tools and equipment that produce filters for multiplexers and demultiplexers can produce gain equalization filters for EDFA and Raman amplifiers. The latter may not be easily realized in AWGs, Echelle gratings, or FBT couplers.

We have shown that there exists a trend toward steeper and wider filters and CWDM filters. Several high energy PVD processes have been employed for the deposition of these filters. Each has some advantages and disadvantages. However, the disadvantages are continually being resolved by filter manufacturers and are often kept as trade secrets.

8. ACKNOWLEDGEMENTS

Many thanks to, Mark Farries, Kelly Olson, Heidi Pinkney, Margot Walsh, and Edward Williams, all of JDSU, who provided some of the material included in this paper.

9. REFERENCES

1. See for example, Jeff Hecht, *Understanding Fiber Optics*, 3rd Edition, Prentice Hall, 1999. Also, S.V. Kartalopoulos, *Introduction to DWDM Technology*, SPIE Optical Engineering Press, 2000.

2. M. Tilsch, C.A. Hulse, K.D. Hendrix, and R.B. Sargent, "Design and Demonstration of a Thin-Film Based Gain Equalization Filter for C-Band EDFAs," *NFOEC 2000*, 390-395.

3. B. Villeneuve, H.B. Kim, M. Cyr, and D. Gariépy, "A Compact Wavelength Stabilization Scheme for Telecommunication Transmitters,"*1997 Digest of the LEOS Summer Topical Meetings*, 21, 11-15August 1997.

4. François Ouellette, "Fiber Bragg Gratings," *OE magazine*, Vol. 1, Number 1, 38, January 2001.

5. M.K. Smit, and S. van Dam, "PHASAR-Based WDM-Devices: Principles, Design and Applications," *IEEE Journal of Selected Topics in Quantum Electronics*, Vol. 2, No. 2, 236, 1996.

6. F. Gonthier, "Fused Couplers increase system design options," *Laser Focus World*, June 1998.

7. E.S. Koteles, "Integrated Planar Waveguide Demultiplexers for High-Density WDM Applications," *Fiber and Integrated Optics*, 18, 211, 1999.

8. GR-1221-CORE, "Generic Reliability Assurance Requirements for Passive Optical Components," *Bellcore*, Issue 2, January 1999.

9. H.A. Macleod, *Thin Film Optical Filters*, 2nd Edition, MacMillan Publishing Co., NY, 1986.

10. H. Takashashi, "Temperature stability of thin film narrow bandpass filters produced by ion assisted deposition," *Applied Optics*, Vol. 34, 667, 1995.

11. Zöller, S. Beißwenger, R. Gotzelmann, and K. Matl, "Plasma ion assisted deposition: A novel technique for the production of optical coatings," *Proceeding of SPIE*, Vol. 2253, 395, 1994.

12. R. Faber, K. Zhang, and A. Zöller, "Design and Manufacturing of WDM Narrow Band Interference Filters," *Proceedings of SPIE*, Vol. 4094, 58, 2000.

13. D. Gibson, "Fast Coatings for DWDM Filters," *Photonics Spectra*, Vol. 35, Issue 2, 114, February 2001.

14. See sales literature from Ion Tech, Inc., www.iontechinc.com.

15. See sales literature from Oxford Instruments, www.oxford-instruments.com.

16. M.A. Scobey, and D.E. Spock, "Passive DWDM components using Microplasma" optical interference filter," *OFC'96 Technical Digest*, 242, 1996.

17. M.A. Scobey, U.S. Patent # 5,851,365, "Low Pressure Reactive Magnetron Sputtering Apparatus and Method," December 22, 1998.

18. H.A. Macleod, "Turning value monitoring of narrow-band all-dielectric thin-film optical filters", *Optical Acta* **19**, 1-28, 1972.

19. P. Bousquet, A. Fornier, R. Kowalczyk, E. Pelletier, and P. Roche, "Optical Filters: monitoring process allowing the auto-correction of thickness errors," *Thin Solid Films* **13**, 285-290, 1972.

20. J. Campbell, "Coarse WDM makes waves in metro/access markets," *WDM Solutions*, 23, November 2000.