

Chirped fiber Bragg gratings equalize gain

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The successful deployment of WDM systems is directly related to the emergence of high performance optical amplifiers. Flat-gain optical amplifiers over the whole communication bandwidth are thus needed to ensure proper amplification of every channel in WDM communication systems. To perform amplifier gain equalization, one of the options is to insert within the amplifier a gain flattening filter (GFF) precisely tailored to the inverse gain curve.

Several GFF technologies can be used to perform the task of gain equalization. Among those, thin film dielectric filters, sinusoidal filters and fiber gratings (Bragg and long period) are presently offered on the market. Among the requirements, these filters must match as closely as possible the inverse gain curve of the individual amplifiers, introduce very low polarization dependence, minimize the gain deviation in a cascade of amplifiers, have a small package footprint and be easily manufactured in high volume quantity. Also, the technology that will prove to be best should be low-cost and not dependent on a unique technology such as a special fiber. Table 1 presents a comparison of some of the most popular GFF technologies commercially available.

	Thin film filter	Micro-optic sinusoidal filter	Long-period fiber grating	Chirped fiber Bragg grating
Fit to the inverse gain curve (error function)	+/-0.5 dB	+/-0.2 dB	+/-0.5 dB	+/-0.1 dB
PDL	<0.1 dB	<0.1 dB	<0.2 dB	<0.1 dB
PMD	NA	<0.05 ps	NA	<0.1 ps
Insertion loss (out of band)	1 dB	1 dB	0.2 dB	0.1 dB
Back reflection	Low	Low	Low	High
Wavelength dependence vs temperature	<5 pm/°C	<3 pm/°C	<3 pm/°C	<1 pm/°C
Dimensions	small	small	large	small

Table 1: Comparison of optical amplifier GFF technologies.

Among the technologies presented in table 1, thin film filter is the most proven and mature technology. Typical thin film GFFs are based on resonant cavity design and are packaged with GRIN lens collimators. They can be used either in reflection or in transmission mode. Complex GFFs can be obtained by using a cascade of multiple simple filters or by accordingly designing a more complex single filter since in theory any filtering function can be obtained using an interference coating [1]. Although this last option reduces the packaging complexity, it suffers from a complex fabrication process (hundreds of coating layers) and is not easily adaptable to new gain profiles. Moreover, thin-film GFF being a bulk technology, insertion loss can be in excess of 1 dB for complex gain profile.

Sinusoidal filters e.g. Mach-Zehnder devices can be made using different technologies such as fused biconic tapers (FBT), planar lightwave circuit (PLC) or micro-optic. As the name implies, these filters have a sinusoidal function where the free spectral range (FSR) is adjusted to cover the desired operating window of the amplifier. Fourier analysis of the EDFA gain spectra allows to determine the number and the depth of the filters needed. To cover the complete EDFA C-band, usually three to five sinusoidal filters are required. This large number of filters greatly increases the packaging size and complexity. Also, this technology has yet to be proven for high volume field deployment.

Fiber grating-based GFFs filters can be divided in two categories: long-period and Bragg gratings. In long-period gratings (LPG), a periodic structure much greater than the signal wavelength (on the order of 200 to 400 μm) is formed in the core of a photosensitive fiber [2]. In this type of structure, light interacting with the grating is coupled into forward propagating cladding modes where it is rapidly attenuated due to absorption and scattering. This wavelength selective lossy device has the main advantage of having very low back reflection thus avoiding the use of optical isolators when incorporated within the amplifiers. However, as for sinusoidal filters, many gratings are required to cover the full EDFA bandwidth thus increasing the manufacturing processes. Moreover, the wavelength of operation of an unpackaged long-period grating is very sensitive to temperature drift by a factor at least five times larger ($\sim 50 \text{ pm}/^\circ\text{C}$) than Bragg grating. To reduce this temperature sensitivity, writing the LPG in a special fiber may be required. In addition to temperature sensitivity, LPGs are also very sensitive to bending losses. All these factors combined together greatly add complexity to the athermal packaging design.

Spectrally designed Bragg gratings (tilted or chirped gratings) are other options that are gaining more and more popularity as gain-flattened optical amplifiers are deployed in the field. For tilted Bragg gratings, the interference fringes are slanted while the grating is being written. Most of the guided mode interacting with the grating is coupled into radiation modes in a counter-propagating direction. Tilted Bragg gratings used as GFFs [3] have thus the main advantage of having low residual back reflection level. When this level is sufficiently low, this avoids the use of an optical isolator when the filter is incorporated in the amplifier. For complex equalization gain profile, multiple tilted Bragg gratings are required. Although these types of gratings have shown adequate gain equalization performances, they may be difficult to reproduce in a controlled manner.

GFFs using chirped fiber Bragg gratings (CFBG) have been successfully demonstrated [4] and could prove to be an optimal choice for gain equalization. These reflective filters are fabricated by changing the period of the untilted interference fringes along the length of the grating while adjusting the refractive index modulation to match the required transmission loss at a specific wavelength. For gain flattening application, these filters are usually used in a transmission mode. These all-fiber filters can be fabricated in compatible standard single-mode fiber leading to very low splicing losses with conventional fiber such as SMF-28. Polarization maintaining fiber such as PANDA or elliptical core type can also be used to write the grating when a flat-gain polarization maintaining EDFA is to be designed. Moreover, being an all-fiber technology, out of band insertion loss for these devices is kept below 0.1 dB and is mainly introduced by the UV-induced index change in the fiber obtained during the writing process. With an appropriate annealing process, these devices can be made very stable leading to a service lifetime exceeding 25 years [5]. In comparison to most other gain-flattening solutions, only one filter is required to cover a very large optical bandwidth ($>35 \text{ nm}$) leading to a very small package footprint.

It is important to mention that the process used to fabricate these types of GFFs is very flexible and can be adjusted very rapidly to new gain profiles. For optical amplifier designer, this is a very cost effective and attractive solution since this can lead to very short GFF prototyping development time. In a manufacturing environment, automated processes dedicated to high-volume production of these GFFs are already available to sustain the actual gain-flattened optical amplifier market growth.

One of the main features of these filters is the very small error function that can be obtained relative to the inverse gain curve of the optical amplifiers over a wide optical bandwidth. This small error function is extremely important when GFFs are used in a cascade of amplifiers. This avoids large signal-to-noise discrepancy among the WDM channels that may lead to significant sensitivity penalty at the receiver. Figure 1 shows EDFA gain equalization from 1526 to 1562 nm when a CFBG used in transmission is incorporated within the amplifier. Although the maximum gain deviation for this amplifier is 8 dB, an error function as small as $\pm 0.1 \text{ dB}$ is obtained over 36 nm. The figure inset shows the shape of the filter used to flatten this amplifier. This filter was packaged in a very small cylindrical athermal housing (55 x 4.8 mm) with smaller than $1 \text{ pm}/^\circ\text{C}$ from -20 to $+70 \text{ }^\circ\text{C}$. This low GFF wavelength dependence against temperature is extremely important since a small wavelength drift particularly where the slope of the filter is very steep can be very detrimental to the gain shape of the amplifier.

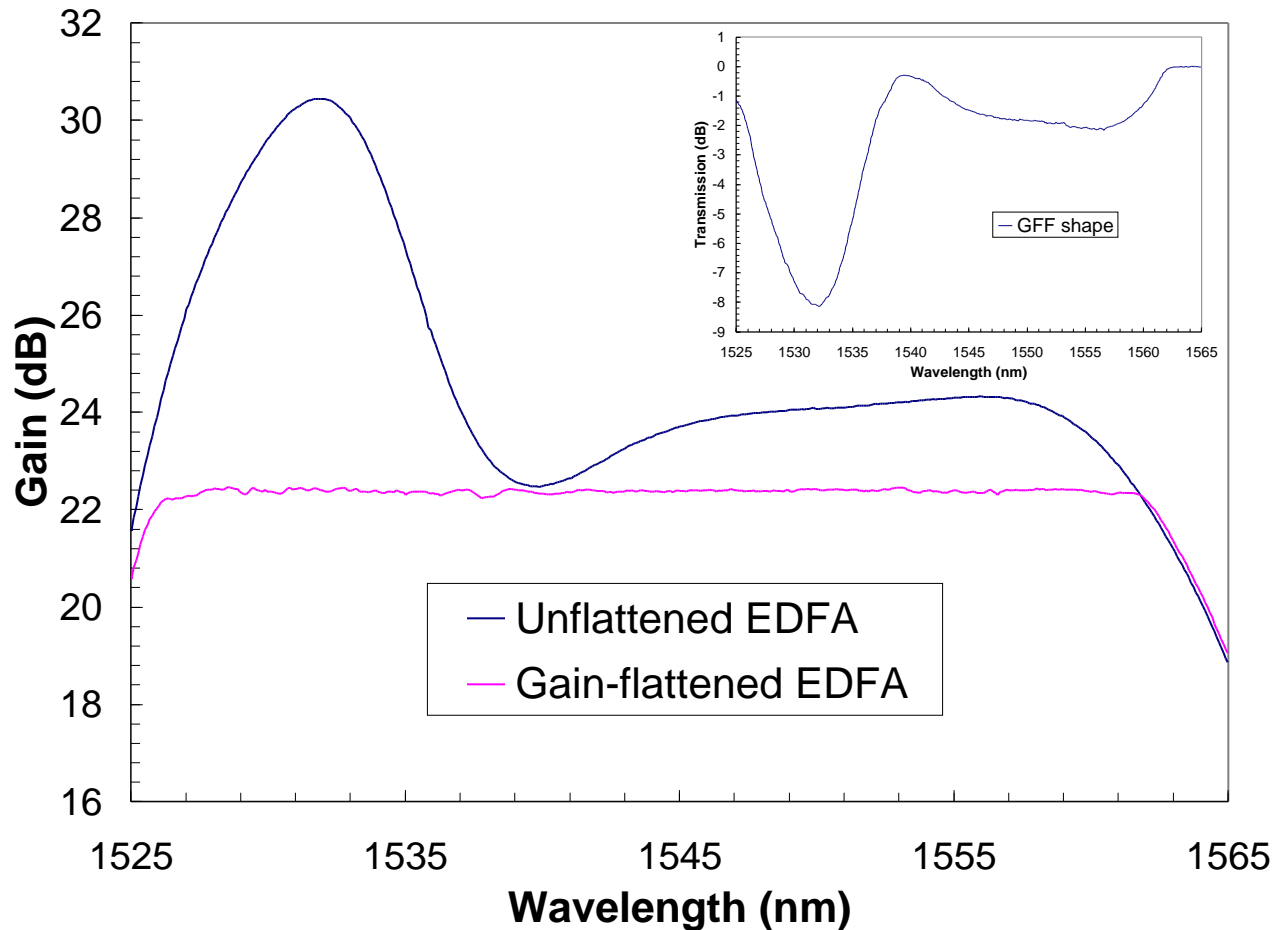


Figure 1: Gain equalization performances with CFBG-based GFF. The figure inset shows the shape of the GFF used to obtain the gain-flattened EDFA.

Since CFBG-based GFFs are reflective filters usually used in transmission, they must be combined either with isolators or circulators for efficient operation within an optical amplifier. This insures that no significant gain or noise figure degradation is observed [4]. One may argue that the use of an additional optical isolator is detrimental to the net gain of the amplifier. However, it has been shown that when the filter is incorporated in the middle of a two-stage amplifier the losses induced by the additional optical isolator are compensated in the second stage of the amplifier [4].

When designing an optical amplifier, the polarization dependent loss (PDL) and polarization mode dispersion (PMD) of the numerous optical components used in the amplifier must be kept to a minimum. This is particularly important when optical amplifiers are used in a cascade configuration with bit rate larger than 10 Gb/s. Typically, when the manufacturing processes of the CFBGs are well mastered, PDL is kept below 0.1 dB for GFF similar to the one presented in figure 1. Furthermore, for negligible UV-induced birefringence, typical value of PMD obtained for these types of GFFs is smaller than 0.1 ps.

Another important aspect that must be considered when inserting GFFs in optical amplifiers used in a cascade configuration is the cumulative effect of the error function of the individual filters. In the case where individual GFF incorporated in the optical amplifiers of a chain are similar, the error will accumulate in a linear fashion. For example, let's assume that GFFs manufactured using a technology such that they all present exactly the same error function of ± 0.25 dB are incorporated in five optical amplifiers to be cascaded. In the worst-case situation, at the output of the amplifiers chain, the largest power deviation between the strongest and the weakest channel will be 2.5 dB. For long cascade of amplifiers (in

submarine systems, it is not unusual to cascade 100 to 200 amplifiers), this can lead to large unacceptable bit error rate (BER) discrepancy among the channels. On the other hand, CFBG-based GFFs can be manufactured in a way such that the error function will not accumulate in a linear fashion when the filters are cascaded; this has the effect of greatly reducing the power discrepancy among the strongest and weakest channel in a long cascade of amplifiers. Figure 2 presents the results obtained when five different CFBG-based GFFs are summed and averaged numerically. Figure 2b clearly demonstrates that although the error function of each individual GFF is within ± 0.25 dB (Figure 2a), the average of the summed individual error function is accurate within ± 0.1 dB. For this reason, CFBG technology seems particularly well suited when filter cascading effect is a main concern.

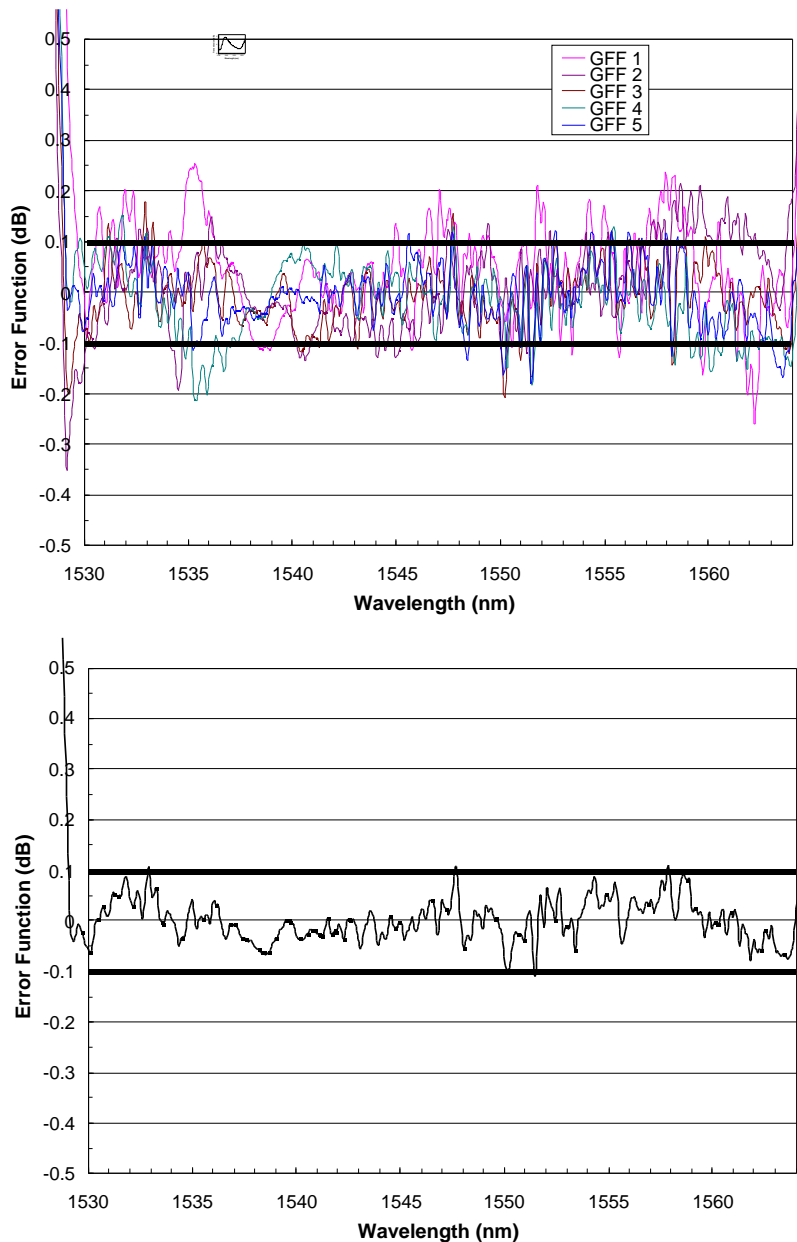


Figure 2: Effect of cascading five CFBG-based GFFs. The top graph presents the five individual error functions accurate within ± 0.25 dB (the insert shows the target profile), while the bottom example averages the sum of the five individual error functions, showing an accuracy of ± 0.1 dB.

Although many GFFs technologies are presently commercially available, it is clear that the best GFF solution will be dictated by the optical amplifier manufacturers stringent requirements. Optimal match with the inverse gain curve is certainly of prime importance. All-fiber technology such as CFBGs is perfectly suited to achieve minimal error function, while keeping undesirable effects such as PDL, PMD and temperature dependencies to a minimum level. CFBG manufacturing process is flexible enough that new GFF profiles can be rapidly available for quick amplifier performance adjustments. But more importantly, high quality CFBG can be manufactured in volume to meet the constantly increasing market demand.

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