Gain-Flattening Filters with Autonomous Temperature Stabilization of EDFA Gain

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ABSTRACT With the steadily increasing demand for fiber-optic communications, hope is more and more being placed in the method known as wavelength division multiplexing, or WDM. The key device supporting WDM technology is the erbium-doped fiber amplifier (EDFA), and such amplifiers need to have a flat gain spectrum. A problem arises, however, in the fact that the loss profile and gain spectra of erbium-doped fiber are temperature dependent, resulting in temperature-dependent changes in the EDFA gain spectra. The authors took note of long-period fiber gratings having a large wavelength shift temperature dependence, and have combined the grating with a conventional gain-flattening filter (GFF) in a compound GFF that provides stabilization of EDFA gain spectra over a wide range of temperatures.

1. INTRODUCTION

With widespread use of Internet services, major attention has focused in recent years on wavelength division multiplexing (WDM), a technique whereby optical signals of a number of different wavelengths are multiplexed for transmission. The erbium-doped amplifier (EDFA) is a key device in WDM systems. Its comparatively wide wavelength range of amplification allows it to provide batch amplification of the signals within the wavelength range, making it essential as an amplifier of transmission in WDM systems.

In WDM systems the deviation in power level of the signals causes a decrease in transmission distance and wavelength range, requiring that the EDFA gain spectra be flat within the signal range. EDFAs, however, make use of input signal amplification by stimulated emission from erbium ions, so that, reflecting the fine structure of ion energy levels, the gain spectra have an asymmetrical twin peaks within the amplification range. The usual way to flatten gain is to use a gain-flattening filter (GFF), and the EDFA gain is flattened by inserting into it a fiber having a loss profile that is the reverse of the gain spectra of the EDF.

There is, however, a temperature-dependent wavelength shift in the loss profile of the GFF, and there is also a temperature dependence in the EDF gain spectra. This means that for EDFAs, temperature dependence is particularly large in the region of 1530 to 1535 nm [1]. Currently steps are being taken to stabilize gain by controlling the temperature of the EDFA as a whole, but there are problems in terms of unit size and power consumption, raising calls for a technological breakthrough.

In this study the authors took note of long-period fiber gratings, which have a large wavelength shift temperature dependence [2], and have combined the grating with a conventional gain-flattening filter in a compound GFF that provides stabilization of EDFA gain spectra over a wide range of temperatures [3]. This paper discusses on the principle of temperature stabilization of gain, and reports on the fabrication of a prototype.

2. TEMPERATURE-DEPENDENCE OF GAIN IN CONVENTIONAL EDFAs

Normally, the flattening of EDFA gain is accomplished by introducing an optical GFF having a loss profile that is the reverse of the gain spectra of EDF. A number of types of optical GFF have been proposed --using etalon filters [4)-6)], dielectric filters [7)], long-period fiber gratings [8)], Mach-Zehnder silica waveguides [9)], split-beam Fourier filters [10)], and so on.

In all of them, there normally occurs a wavelength shift in the loss profile due to changes in the temperature of the medium. And while the gain spectra of EDF is also dependent on temperature, it accords with changes in ion energy levels, so that the shape of the gain spectra changes with temperature, but does not manifest itself in the form of a wavelength shift.

Figure 1 shows a typical example of the temperature

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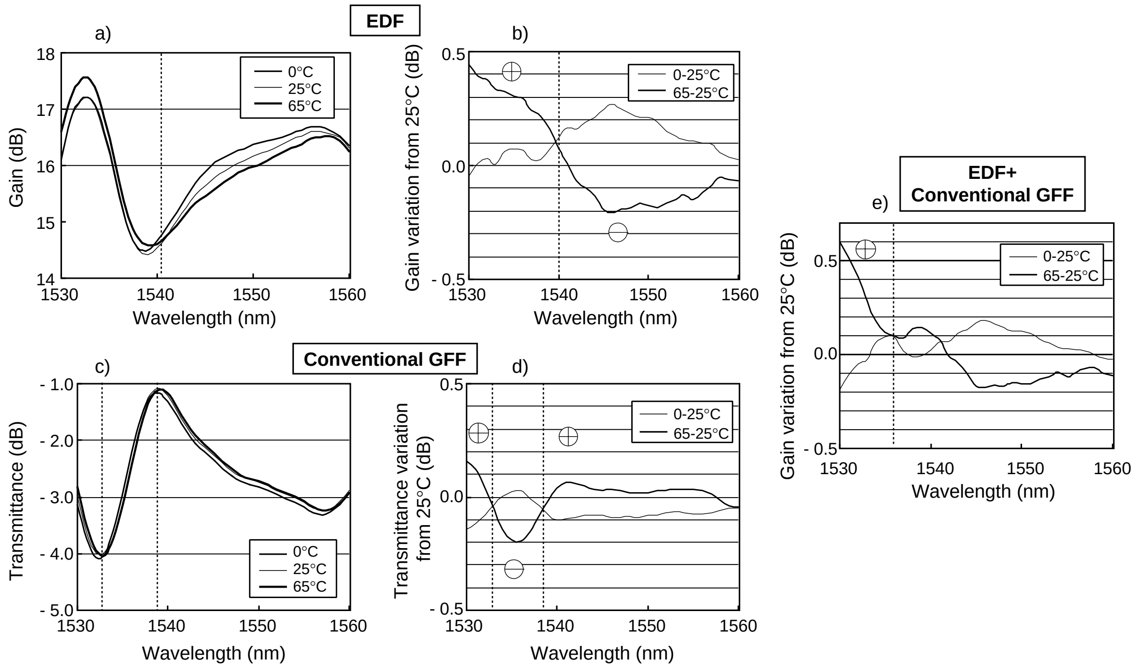

Figure 1 Temperature dependence of EDF and GFF

dependence of the gain spectra of an EDF and the loss profile of an optical gain-flattening filter (GFF). Here the amount of increase in EDFA gain due to temperature rise is defined as the temperature coefficient, and is given a positive value when gain increases with a rise in temperature, and a negative value when it decreases. The plus signs (+) in the figure show the wavelength range in which the temperature coefficient is positive, and the minus signs (-) show the range in which it is negative. The temperature coefficient of the gain spectrum of the EDF is positive below 1540 nm and negative above that wavelength, whereas a temperature-dependent wavelength shift toward the positive direction can be observed for the optical GFF, so that the temperature coefficient is positive at wavelengths of 1535 nm and below, negative at from 1535 to 1540 nm, and positive above 1540 nm. Thus in an EDFA combining EDF gain and an optical GFF, the temperature dependence of the EDF gain spectra and of the loss profile of the optical GFF cancel each other out at wavelengths above 1535 nm, whereas at wavelengths below 1535 nm, their temperature dependences are mutually reinforcing (see Figure 1-e).

Recently a dielectric filter type of GFF has been developed in which temperature dependence of the wavelength shift is made virtually negligible by adjusting the stress between the dielectric membrane and the substrate, but since in this design there is a residual temperature dependence of EDF gain, no complete solution can be achieved. Attempts have also been made to stabilize gain by controlling the temperature of the entire EDFA, but this has presented problems in terms of unit size and power consumption.

3. TEMPERATURE STABILIZATION USING LONG-PERIOD GRATINGS

3.1 Temperature Dependence

The temperature dependence of filters other than long-period fiber filters may be expressed as the wavelength shift due to temperature T at a given wavelength λ using the interference width l and the refractive index n

$$\frac{\mathrm{d}\lambda}{\mathrm{d}T} = \lambda\left(\frac{1}{l}\cdot\frac{\mathrm{d}l}{\mathrm{d}T} + \frac{1}{n}\cdot\frac{\mathrm{d}n}{\mathrm{d}T}\right)$$

The first term relates to the coefficient of linear expansion and the second to the temperature dependence of the refractive index, and both are positive for ordinary glass. For ordinary GFFs, the wavelength shift due to temperature is about 0.010 nm/°C at most. In dielectric multilayers it is necessary to add another term for the temperature dependence of the stress between the multilayer and the substrate, and this term can be made negative by controlling the linear expansion coefficient of the substrate so that the temperature coefficient can be made to approach zero indefinitely. But even if the temperature coefficient of the GFF is zero, there will be a residual temperature dependence of EDF gain, making it impossible to achieve an EDFA with a low overall temperature dependence of gain.

The temperature dependence of a long-period fiber grating, on the other hand, may be expressed as a wavelength shift at center wavelength λ_c caused by temperature T, using grating pitch Λ, the effective refractive index of the fiber in guided mode n_{core}, and the effective refractive index in the mth clad mode n_{cladm}, according to the following Equation [11]

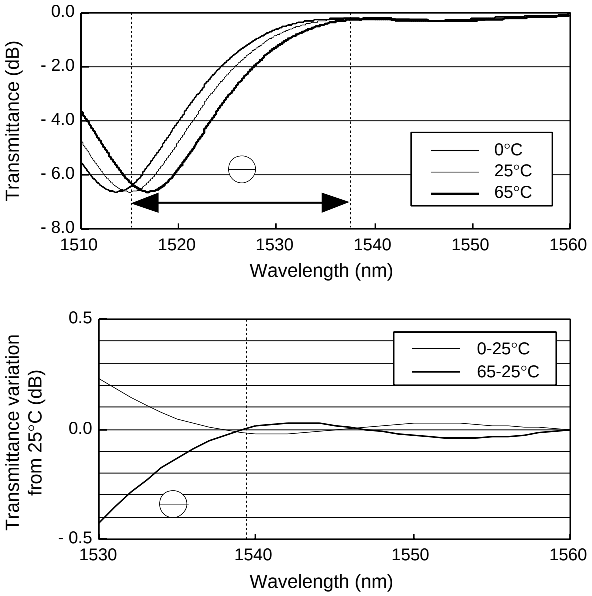

Figure 2 Temperature dependence of long-period fiber grating

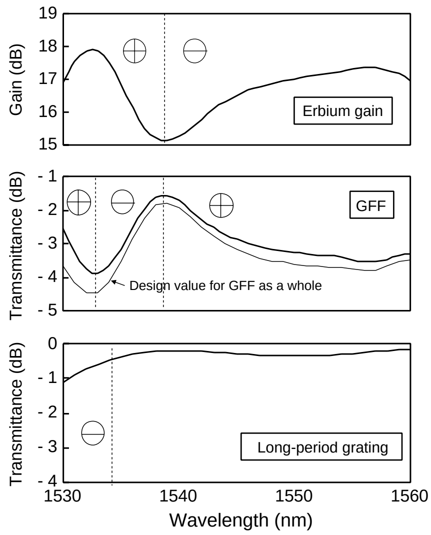

Figure 3 Characteristics of a GFF with long-period fiber grating

$$\frac{\mathrm{d}\lambda_c}{\mathrm{d}T} = (n_{\mathrm{core}} - n_{\mathrm{cladm}})\frac{\mathrm{d}\Lambda}{\mathrm{d}T} + \Lambda\left(\frac{\mathrm{d}n_{\mathrm{core}}}{\mathrm{d}T} - \frac{\mathrm{d}n_{\mathrm{cladm}}}{\mathrm{d}T}\right)$$

The first term, relating to the coefficient of linear expansion, is about the same magnitude as for an ordinary GFF, but the second term, which relates to the temperature dependence of the effective refractive index in guided and clad mode, Λ will be about 100 μm, as compared to λ/n of about 1 μm for an ordinary GFF. This means that for long-period fiber gratings, the temperature coefficient is larger. When a grating is made using ordinary fiber, the wavelength shift due to temperature for long-period fiber gratings is about 0.050 nm/°C, which is larger than for ordinary GFFs. Reducing the temperature coefficient would normally entail addition of a dopant to the fiber [11] or the use of a temperature-compensating package, but in the present work a long-period fiber grating with a large temperature coefficient was used without modification to stabilize the temperature dependence of gain for the EDFA as a whole.

3.2 Principle of Temperature Stabilization in a Long-Period Fiber Grating

Temperature stabilization of EDFA gain requires a filter having a negative temperature coefficient in the range of wavelengths below 1535 nm, where the temperature dependence of gain presents a problem. Since the wavelength shift in characteristics due to filter temperature rise is normally in the long-wavelength direction, we need a filter having characteristics with a slope that is the reverse of the loss profile of the GFF at wavelengths below 1535 nm. It is possible to compensate for the temperature dependence of the EDFA gain spectra by combining a long-period fiber grating having a large temperature coefficient, using it as a reverse-slope filter, with an ordinary GFF having a small temperature coefficient.

When a filter having characteristics with a slope the reverse of the loss profile of an optical GFF is to be used for temperature stabilization, gain flattening must be carried out so as to include a temperature-stabilized component. Since the temperature coefficient of the long-period fiber grating is large, compensation for temperature dependence can be effected by a filter with a small reverse slope, and the amount of flattening GFF gain is smaller. Figure 2 shows typical temperature dependence of a long-period fiber grating. It can be seen that to achieve a temperature stabilizing component of 0.4 dB from 25 to 65°C at 1530 nm, a transmittance loss of about 1 dB is ample.

Figure 3 shows the characteristics of the components of a temperature-stabilized EDFA with long-period fiber grating. To flatten EDFA gain, the GFF must also be provided with a loss profile obtained by subtracting the loss component of the long-period fiber grating from loss that is the reverse of the wavelength dependence of EDF gain. The long-period fiber grating used to compensate for the temperature dependence of the EDFA gain spectra has a loss at 1530 nm of about 1 dB, so that the loss profile of the GFF is not substantially different from loss profile required when the GFF stands alone.

Since the temperature dependence of the loss profile of the long-period fiber grating increases on the short-wavelength side at 1540 nm or less, temperature stabilization for EDFA gain can be effected at wavelengths below 1535 nm, a range that presented problems in the past. Further, at wavelengths above 1540 nm, the loss profile of the long-period fiber grating is less temperature-dependent. Thus conventionally there was no effect in the range in which the temperature dependences of the EDF gain spectra and of the GFF loss profile cancel each other, while it is desirable that, for the canceling effect, that there still be a certain amount of wavelength shift in the GFF.

4. PROTOTYPE

4.1 Appearance

Figure 4 is a photograph of a long-period fiber grating module used in a temperature-stabilized GFF. It measures 47 mm in length by 3.5 mm in diameter. The GFF is the same as the grating module in appearance and size.

4.2 EDFA Configuration

Figure 5 shows the configuration of the EDFA with autonomous temperature stabilization used in the prototype. Normally, gain flattening is accomplished by connecting the optical GFF in series with the EDF. In the present work a GFF and long-period grating were series connected in the center portion of a two-stage EDFA. The prototype EDFA had a gain of 13 dB.

Figure 4 Photograph of long-period fiber grating module

4.3 Prototype Characteristics

Figure 6 shows the characteristics of the prototype. The period of the fiber grating was 400 μm, and the fourth clad mode was used. The temperature dependence of wavelength shift was 0.006 nm/°C for the GFF and 0.050 nm/°C for the long-period fiber grating.

It can be seen that the GFF of Figure 6 exhibits the loss profile of a compound GFF consisting of a GFF plus long-period fiber grating, and that it has a temperature dependence that is the reverse of EDF gain. There is a particular improvement at wavelengths below 1535 nm, where EDFA gain temperature dependence has constituted a problem, and the temperature dependence of gain between 0 and 65°C was 0.25 dB, in contrast to 0.79 dB before stabilization. Further, gain flatness was 0.60 dB or less for all temperatures from 0 to 65°C.

A prototype was also fabricated for an EDFA with a gain of 26 dB, and between 0 and 65°C, a result of 0.45 dB was obtained for the temperature dependence of gain for the EDFA as a whole.

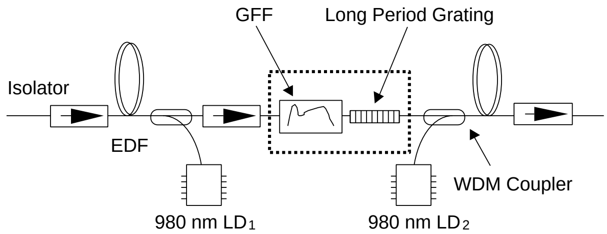

Figure 5 Configuration of EDFA with autonomous temperature stabilization

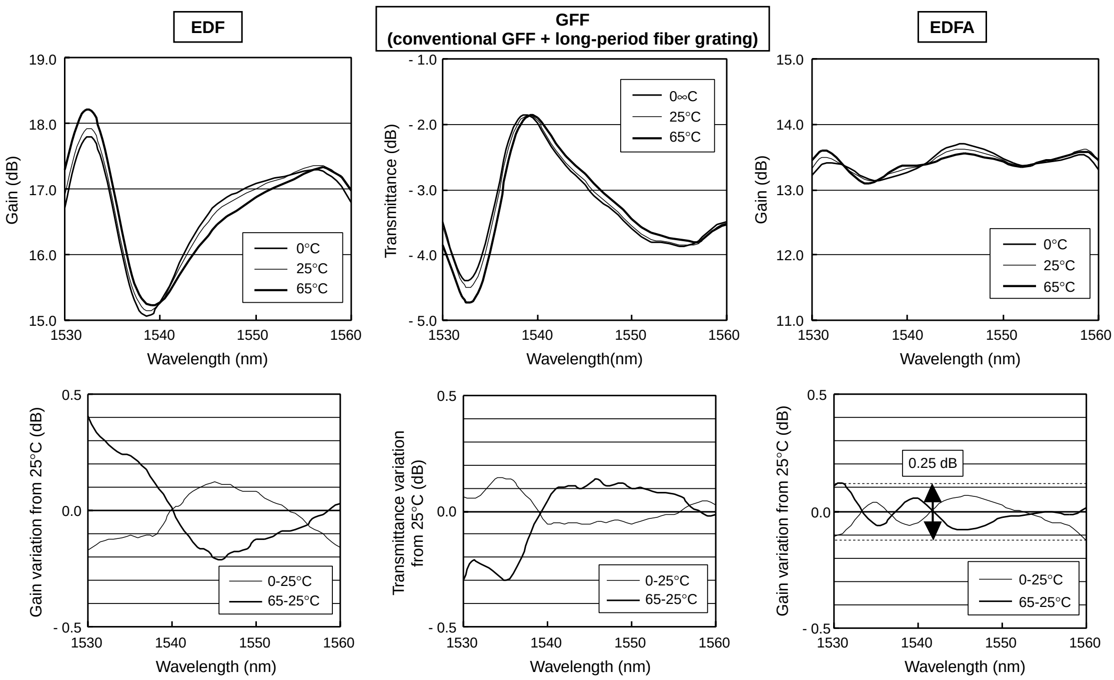

Figure 6 Characteristics of EDFA used in a prototype GFF with autonomous temperature stabilization of Erbium gain

5. CONCLUSION

In the past the problem of EDFA gain temperature dependence, arising from the temperature dependence of the gain spectra of EDF and of the loss profile of gain flattening filters, has presented a problem. By incorporating an ordinary gain flattening filter (GFF) and a long-period fiber grating having a large temperature coefficient, a compound GFF has been realized that stabilizes the temperature dependence of EDFA gain over a wide range of temperatures.

Prototypes of compound GFFs have been fabricated for two types of EDFA, and the temperature stabilizing effect of long-period fiber gratings has been confirmed. The temperature dependence of EDFA gain between 0 and 65°C was 0.25 dB for the EDFA with a gain of 13 dB, and 0.45 dB for the EDFA with a 26-dB gain, confirming the feasibility of fabricating EDFAs having gain of low temperature dependence.

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