Erbium Doped Fiber Amplifier with Passive Temperature Compensation

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Abstract: A commercially viable technique for passive temperature compensation in EDFAs based on a MZ interferometer with a variable splitting ratio is developed and described. It allows system engineers to simultaneously achieve better gain flatness, small size, low power consumption and heat production.
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1. Introduction:

Network carriers continue to face increased bandwidth and capacity demand in metro, regional, and long-haul networks as the traffic almost doubles year on year.

Systems using 100Gb/s per-channel bit rate optical transport are widely deployed and channel capacity beyond 100 Gb/s is now under active research and development to sustain traffic growth, improve spectral efficiency, and lower the cost per bit in fiber transmission. Since optical amplifiers are the dominant noise source in transmission system design and with the introduction of ROADMs the number of optical amplifiers is almost doubled the most effective method of improving system OSNR performance is to optimize the amplifier noise performance[1].

2. Relation of amplifier gain ripple and system OSNR performance

In a simple long haul system, multi-wavelength signals pass through several spans and amplifiers. For N spans, the number of optical amplifiers is N +1. The target average gain of each amplifier is equal to the span loss in order to maintain the average optical power. Although the OSNR performance increases with increasing launch power, the system performance is limited by nonlinear effects and typically the launch power target is less than 3dBm/ch.

The total ASE noise at the output port of the last amplifier is the sum of the ASE power produced by all amplifiers:

$$\begin{aligned} P_{ASE}^{T}(\lambda) &= 10\log\left(\sum_{i}^{N} 10^{(G_i(\lambda)-58+NF_i)/10}\right) \\ G_i(\lambda) &= IL_i^{span} + G_i^{er}(\lambda) \\ P_{ASE}^{T}(\lambda) &= 10\log\left(\sum_{i}^{N} 10^{(IL_i^{span}+G_i^{er}(\lambda)-58+NF_i)/10}\right) \end{aligned} \tag{1}$$

Where $G_i^{er}(\lambda)$ is the gain error for each channel when the average gain of the ith amplifier gain set to equal to loss of the ith span. Signal power at output port of the last amplifier is:

$$P_S^{last}(\lambda) = P_S^o - \sum_{i}^{N}(G_i(\lambda) - IL_i^{span}) = P_S^o - \sum_{N} G_i^{er}(\lambda) \tag{2}$$

The signal power does not go back to the initial level because of the accumulated gain error. For simple discussion, assume an optical transmission system consists of N equal spans and all the amplifiers are identical. This also means that the gain ripple in this system accumulates:
So that OSNR at the output port of the last amplifier which is same as the received OSNR is:

$$OSNR(\lambda) = P_S^o + (N-1)G^{er}(\lambda) + NF - IL^{span} + 10\log N - 58 \tag{3}$$

Considering the worst scenario that the channel with lowest gain which has half GR lower than average gain .

$$OSNR(\lambda_{Min}) = P_S^o - \frac{(N-1)GR}{2} + NF - IL^{span} + 10\log N - 58 \tag{4}$$

Where GR (peak-peak gain ripple) is one of the main amplifier specification describing gain flatness of an amplifier. One can easily find that there are three ways to improve OSNR performance, increasing launch power as mentioned above, reducing NF of each EDFA and improving GR of each EDFA. Most well designed EDFAs already have low NFs and there is little room for improvement. There is, however, significant room for improving the GR and this can have significant impact on the system OSNR as it is multiplied by (N-1)/2 in the equation above. For example, GR reduction from 1.5dB to 0.5dB will result in a 4.5dB OSNR improvement in a ten amplifier cascade system. Although the discussion is based on a system with equal span loss, the conclusion for OSNR degradation caused by gain ripple is same for a system with different span losses when the amplifiers have similar gain spectrum.

3. Temperature dependency of the EDFA gain ripple

The gain profile of an EDFA (Erbium Doped Fiber Amplifier) is not flat and changes with temperature. GFFs (Gain Flattening Filters) which have insertion loss proportional to the EDF gain are used to achieve flat EDFA effective gain. GR can be reduced down to 0.5dB with a well designed GFF but only at the temperature for which the GFF is designed.

When the temperature of the EDF changes the gain spectrum shifts as shown in Fig.1. For an L-band EDFA, the temperature dependant gain ripple can be up to 3dB.

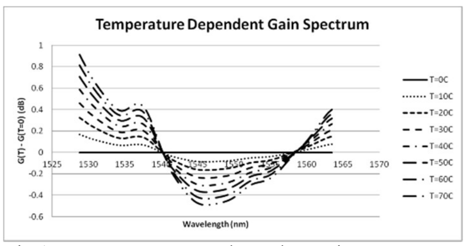

Fig.1 EDFA temperature dependent gain spectrum

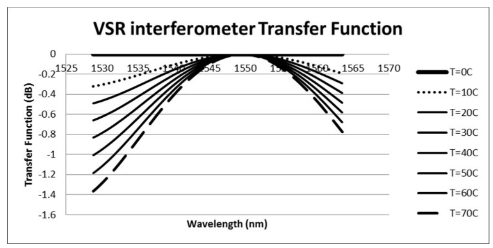

Fig.2 transfer function of variable splitting ratio interferometer

As a passive component, the GFF can do nothing about dynamic gain spectrum changes due to the temperature dependency of the EDF. The most widely used method by all EDFA makers today is to maintain a constant temperature of the EDF under all operational conditions. This is often achieved by putting the EDF coil into an insulated box and heating the inside temperature to the highest working temperature. This results in such a temperature stabilized EDFA having a large form factor, high cost and high power consumption.

What will be proposed below is a temperature compensation technique that does not require temperature stabilization of the EDF and hence eliminates the associated disadvantages.

4. Analyzing the EDFA Temperature dependent gain spectrum and the compensation

Analyzing the temperature dependency shown in Fig.1, one can easily find that the temperature dependency curve is mainly a bending with fixed peak position at any temperature with different amplitude. There are also secondary effects of small tilt and some detail "fast ripple" but the magnitude of these effects are not large. Thus it should be possible to find a compensation device which addresses the main temperature dependency and ignores the second and high order effects. Shown in Fig.2 is the transfer function of an MZ interferometer with variable beam splitting ratio. By selecting the optical path difference and the splitting ratio properly, the interference curve can fit the EDFA temperature dependence very well at any temperature. Shown in Fig.4 is the simulation of compensation result of such a compensator and it shows that the EDFA temperature dependence is almost perfectly compensated with less than 0.2dB remaining temperature dependence.

There are many methods to make a device which has a temperature dependant optical splitting ratio. For example, an OPD (Optical Path Difference) producer on an active device based on MEMs, step motor or a passive device based on thermal expansion of the material. Fig.3 is the block diagram of temperature dependent gain compensator.

The transfer function is

$$\gamma = \frac{P_{out}}{P_{in}} = 1 - 2R(1-R)[1-\cos(2\pi\frac{\Delta L}{\lambda})] \qquad (5)$$

$$P_1 = RP_{in}, P_2 = (1-R)P_{in}$$

Make splitting ratio change with temperature according to $R = k\Delta T = k(T - T_0)$, transfer function as shown in Fig.2 can be achieved.

$$\gamma(\Delta T) = 1 - 2k\Delta T(1-k\Delta T)[1-\cos(2\pi\frac{\Delta L}{\lambda})] \qquad (6)$$

Where k is the temperature coefficient and T_0 is the temperature at which the EDFA with GFF has a flat gain.

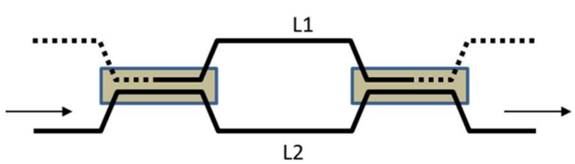

Fig.3 variable splitting ratio MZ interferometer

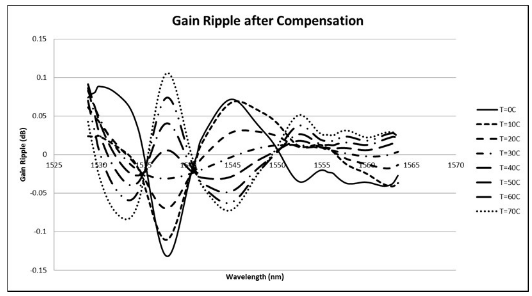

Fig.4 Simulated compensation result

5. Dynamic GFF

The passive temperature compensator we made is based on thermal extension material. It is so small that can be combined with GFF and isolator to form a 3in1 hybrid component without dimension increasing. Such a combination not only saves space, but also reduces insertion loss, BOM cost and manufacturing time.

Fig.5 dynamic 3in1 GFF

Table 1 compare of compensator and heat box

H/C	Gain Flatness	space taking	power consumption	control HW/SW	heat producing	installation time
Heat box	1.1dB	Φ 20x10mm	10W	Y	10W	30min
Compensator	0.8	N/A	N/A	N/A	N/A	N/A

Shown in Fig.6 and Fig.7 are the test result of temperature stabilized EDFA randomly from manufacture. Gain flatness in full operation temperature range is less than 0.7dB for C-band EDFA and 1dB for L-band EDFA.

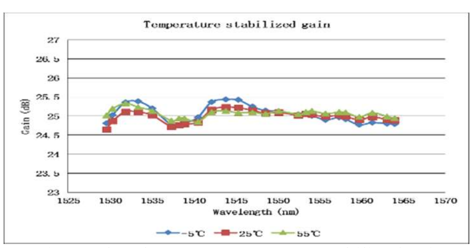

Fig.6 C-band EDFA temperature stabilized gain

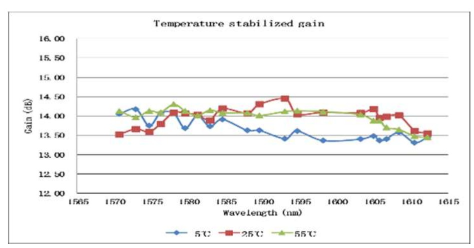

Fig.7 L-band EDFA temperature stabilized gain

Conclusion

Athermal EDFA reduced gain ripple based on a passive temperature dependent gain compensator is presented. The compensation result is better than that with constant temperature method, though there is still some small remaining temperature dependency. The resultant amplifiers have received market acceptance because of the significant advantages compared with those made using the traditional constant temperature method. Using this technique temperature stabilized mini EDFAs have become possible.

[1] John Zyskind, Atul Srivastava, "Optically Amplified WDM Networks", (Elsevier 2011) Chap. 6.