Self-compensation of Spectral Hole Burning Effect in Super C-band EDFA

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Abstract: This work investigates theoretically and experimentally the physical counterpart to the conventional spectral hole burning effect in erbium-doped fiber amplifiers: the inhomogeneous saturable absorption. Using this effect, a cost-effective compensation method is proposed.

1. Introduction

Erbium-doped fiber amplifiers (EDFAs) are the key building block in optical communication networks. Until now, EDFA is still considered as the "best amplifier". It has a gain region that locates in the low-loss window of the silica glass fiber, bandwidth of tens of nanometers, low noise figure and low cost. However, there is still one flaw in the EDFA: its intrinsic gain inhomogeneity which is known as the spectral hole burning (SHB) effect [1]. Under different input channel loadings, the gain profile of the EDFA would be deformed from the full-loading case. The power excursion of the EDFA's output will accumulate throughout the link, leading to a delay of the network reconfiguration as well as bringing additional costs accordingly. Various solutions have been proposed for the compensation of the SHB-induced gain excursion [2,3], but they always come with remarkable cost augmentation.

As the EDFA keeps evolving, the problem of SHB becomes severer. In the past decades, the bandwidth of C-band EDFAs has been continuously expanded from the original 36 nm to the current 48 nm (the *super C-band*). We have observed in experiments that the SHB of the *super C-band* EDFA is significantly higher than the conventional EDFA with narrower bandwidth. *Super C-band* EDFA is achieved mainly by utilizing longer EDF as well as deeper gain flattening filter (GFF), although fine-tailoring the glass composition of the EDF could help to get slightly shallower internal fiber gain ripple. This phenomenon can be explained by Maxim Bolshtyansky's first-order perturbation model of SHB [1]. As will be discussed in the following sections of this paper, for the same target gain level, the magnitude of the SHB effect is generally proportional to the EDF length (the bandwidth would vary accordingly). After all, a cost-effective solution for the suppression of the SHB effect is highly desirable.

In this paper, starting from Maxim's model, we deduce in theory and prove in experiments a rarely discussed physical phenomenon in EDFs: the inhomogeneous saturable absorption (we call it here the inverse SHB (iSHB) for simplicity). By taking advantage of iSHB, we propose a methodology of EDFA design that could lead to the self-compensation of SHB effect within the EDF itself.

2. Theory

Maxim's model (Eq. (1)~(3)) considers the SHB effect as a first-order perturbation to the Giles' homogeneous EDFA model [4], manifested as a measureable 2-D matrix $\Gamma(\lambda_j^{\mathrm{s}}, \lambda^{\mathrm{p}})$. λ^{p} is the wavelength where an imaginary probe signal (or, with negligible low power) is used to detect the fiber gain; λ_j^{s} is the j-th signal wavelength. $\alpha(\lambda^{\mathrm{p}})$ and $g^*(\lambda^{\mathrm{p}})$ are the homogeneous absorption and gain coefficients at the probe wavelength λ^{p}. R_{up} and R_{down} are the upward and downward rates of the Er^{3+} ions, which determines the Er^{3+}'s population distribution in the ground and the metastable levels, N_1 and N_2 (Eq. (3)). The presence of a signal photon flux Q_j^{s} at λ_j^{s} is assumed to induce two first-order (linear) perturbation terms, $R'_{\mathrm{up}}(\lambda^{\mathrm{p}})$ and $R'_{\mathrm{down}}(\lambda^{\mathrm{p}})$, at the probe wavelength λ^{p}, see Eq. (2). The homogeneous $\alpha(\lambda^{\mathrm{p}})$ and $g^*(\lambda^{\mathrm{p}})$ will then be modified into the inhomogeneous pairs: $\tilde{\alpha}(\lambda^{\mathrm{p}})$ and $\widetilde{g^*}(\lambda^{\mathrm{p}})$, see Eq. (1). As a result, the homogeneous gain $G_{\mathrm{homo}}^{\mathrm{dB}}(\lambda^{\mathrm{p}})$ will become the inhomogeneous one, $G_{\mathrm{inhomo}}^{\mathrm{dB}}(\lambda^{\mathrm{p}})$, see Eq. (3).

$$\begin{cases} \tilde{\alpha}(\lambda^{\mathrm{p}}) = \alpha(\lambda^{\mathrm{p}})\left\{1 + \dfrac{R_{\mathrm{up}}R'_{\mathrm{down}}(\lambda^{\mathrm{p}}) - R_{\mathrm{down}}R'_{\mathrm{up}}(\lambda^{\mathrm{p}})}{R_{\mathrm{down}}\left(R_{\mathrm{up}} + R_{\mathrm{down}}\right)}\right\} \\ \widetilde{g^*}(\lambda^{\mathrm{p}}) = g^*(\lambda^{\mathrm{p}})\left\{1 - \dfrac{R_{\mathrm{up}}R'_{\mathrm{down}}(\lambda^{\mathrm{p}}) - R'_{\mathrm{up}}(\lambda^{\mathrm{p}})R_{\mathrm{down}}}{R_{\mathrm{up}}\left(R_{\mathrm{up}} + R_{\mathrm{down}}\right)}\right\} \end{cases} \quad (1)$$

$$\begin{cases} R_{\mathrm{up}} = \sum_j \alpha(\lambda_j^{\mathrm{s}})Q_j^{\mathrm{s}} \\ R_{\mathrm{down}} = \sum_j g^*(\lambda_j^{\mathrm{s}})Q_j^{\mathrm{s}} + \zeta \\ R'_{\mathrm{up}}(\lambda^{\mathrm{p}}) = \sum_j \alpha(\lambda_j^{\mathrm{s}})\Gamma(\lambda_j^{\mathrm{s}}, \lambda^{\mathrm{p}})Q_j^{\mathrm{s}} \\ R'_{\mathrm{down}}(\lambda^{\mathrm{p}}) = \sum_j g^*(\lambda_j^{\mathrm{s}})\Gamma(\lambda_j^{\mathrm{s}}, \lambda^{\mathrm{p}})Q_j^{\mathrm{s}} \end{cases} \quad (2)$$

$$\begin{cases} G_{\mathrm{homo}}^{\mathrm{dB}}(\lambda^{\mathrm{p}}) = 4.34 \times [N_2 g^*(\lambda^{\mathrm{p}}) - N_1 \alpha(\lambda^{\mathrm{p}})] \times L \\ G_{\mathrm{inhomo}}^{\mathrm{dB}}(\lambda^{\mathrm{p}}) = 4.34 \times [N_2 \widetilde{g^*}(\lambda^{\mathrm{p}}) - N_1 \tilde{\alpha}(\lambda^{\mathrm{p}})] \times L \end{cases}, \text{where} \begin{cases} N_2 = \dfrac{R_{\mathrm{up}}}{R_{\mathrm{up}} + R_{\mathrm{down}}} \\ N_1 = \dfrac{R_{\mathrm{down}}}{R_{\mathrm{up}} + R_{\mathrm{down}}} \end{cases} \quad (3)$$

Subtracting $G_{\mathrm{homo}}^{\mathrm{dB}}(\lambda^{\mathrm{p}})$ from $G_{\mathrm{inhomo}}^{\mathrm{dB}}(\lambda^{\mathrm{p}})$ and rearrange the equation using the relations in Eq. (2) and (3), we obtain the expression of Eq. (4), which is the gain deformation induced by the SHB effect. The first observation from

Eq. (4) is that the sign of $\Delta G^{\mathrm{dB}}(\lambda^{\mathrm{p}})$ is determined by the sign of $G^{\mathrm{dB}}_{\mathrm{homo}}(\lambda^{\mathrm{p}})$. If the signal creates a spectral "hole" at λ^{p} when the signal sees gain, it will accordingly create a spectral "bump" at λ^{p} when it sees loss. The former is well known but the latter is rarely mentioned in the literature. We call the latter as the *inverse spectral hole burning* (iSHB) effect, it is esscentially a phenomenon of inhomogeneous saturable absorption.

$$\Delta G^{\mathrm{dB}}(\lambda^{\mathrm{p}}) = G^{\mathrm{dB}}_{\mathrm{inhomo}}(\lambda^{\mathrm{p}}) - G^{\mathrm{dB}}_{\mathrm{homo}}(\lambda^{\mathrm{p}}) = -\frac{g^*(\lambda^{\mathrm{p}})+\alpha(\lambda^{\mathrm{p}})}{R_{\mathrm{up}}+R_{\mathrm{down}}}\sum_j\left\{\Gamma(\lambda_j^{\mathrm{s}},\lambda^{\mathrm{p}})\times Q(\lambda_j^{\mathrm{s}})\times G^{\mathrm{dB}}_{\mathrm{homo}}(\lambda_j^{\mathrm{s}})\right\} \tag{4}$$

Consider the specific case that only one signal $(\lambda^{\mathrm{s}}, Q^{\mathrm{s}})$ and one pump $(\lambda^{\mathrm{pump}} = 976\mathrm{nm}, Q^{\mathrm{pump}})$ are present, Eq. (4) can be reorganized into Eq. (5). It is simply a parabolic function of N_2. Whether the parabolic function opens upward or downward depends on a newly-defined F-factor, which is a function of $Q^{\mathrm{pump}}/Q^{\mathrm{pump}}_{\mathrm{sat}}$.

$$\begin{cases}\Delta G^{\mathrm{dB}}(\lambda^{\mathrm{p}}) = 4.34\dfrac{\Gamma(\lambda^{\mathrm{s}},\lambda^{\mathrm{p}})}{F}\times\{g^*(\lambda^{\mathrm{p}})+\alpha(\lambda^{\mathrm{p}})\}\times\{\alpha(\lambda^{\mathrm{s}})+g^*(\lambda^{\mathrm{s}})\}\times\left\{N_2-\dfrac{\alpha(\lambda^{\mathrm{s}})+F}{\alpha(\lambda^{\mathrm{s}})+g^*(\lambda^{\mathrm{s}})}\right\}\times\left\{N_2-\dfrac{\alpha(\lambda^{\mathrm{s}})}{\alpha(\lambda^{\mathrm{s}})+g^*(\lambda^{\mathrm{s}})}\right\}\times L \\ F = \dfrac{g^*(\lambda^{\mathrm{s}})\left(Q^{\mathrm{pump}}/Q^{\mathrm{pump}}_{\mathrm{sat}}\right)-\alpha(\lambda^{\mathrm{s}})}{\left(Q^{\mathrm{pump}}/Q^{\mathrm{pump}}_{\mathrm{sat}}\right)+1}, \text{where } Q^{\mathrm{pump}}_{\mathrm{sat}} = \zeta/\alpha(\lambda^{\mathrm{pump}}) \text{ is the saturation photon flux at the pump wavelength.}\end{cases} \tag{5}$$

Fig. 1(a) plots the F-factor w.r.t. the pump power at 976 nm and $Q^{\mathrm{pump}}/Q^{\mathrm{pump}}_{\mathrm{sat}}$. The Giles parameters of the EDF used in this calculation were experimentally extracted from CorActive's L1500 alumino-silicate EDF. It can be seen that the F-facotr is very close to a two-valued function: when the pump is off, F converges to $\alpha(\lambda^{\mathrm{s}})$, on the other hand, when the pump is on, it quickly converges to $g^*(\lambda^{\mathrm{s}})$ as the pump power increases. Eq. (5) indicates that the iSHB effect can be triggered by playing with the pump power within the fiber.

To validate the above-mentioned theoretical analysis, we measured the SHB spectra at different N_2 values using the spectrum subtraction technique [1], over 1 meter of L1500 EDF. One single saturation tone at 1532 nm was used to control N_2 as well as to create the inhomogeneous gain deformation. A probe signal with power < -35 dBm was wavelength-swept in order to detect the gain profile. The upper figures of Fig. 1(b) and (c) plot the typical spectra of SHB (with pump) and iSHB (without pump). They almost mirror each other across the line of $\Delta G = 0$ dB. The lower figures of Fig. 1(b) and (c) compare the measured SHB depths at 1532 nm to the parabolic function of Eq. (5) (Γ=0.2). Although the theory is based on the assumption of uniform inversion distribution, the theory and the measurements still show a good matching. Note that Eq. (5) also indicates that the magnitude of SHB is proportional to the EDF length. For *super C–band* EDFA, longer fiber is needed to get the same target gain level, thus the SHB will augment proportionally. More detailed discussion on the physical properties of SHB will be published elsewhere.

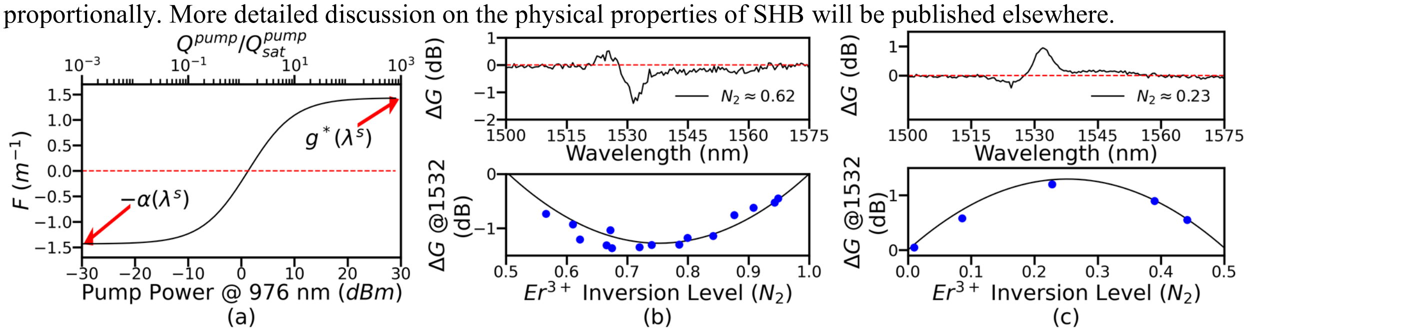

Fig. 1. (a) F-factor as a function of the pump power @ 976 nm and as a function of $Q^{\mathrm{pump}}/Q^{\mathrm{pump}}_{sat}$; (b) *upper*: the SHB spectrum measured with pump power on and with one single saturation tone at 1532 nm, the estimated Er^{3+} inversion level is ~0.62; *lower*: the measured (blue dots) SHB depths at 1532 nm and the fitting using Eq. (5); (c) is of iSHB, similar to (b) but with the pump power off.

2. Self-compensation of SHB

In a conventional EDFA design, the pump power injected into the EDF will decrease in a smooth way along the fiber, from a few hundreads of mW, until serveral mW. Most of the EDF sections work in the conventional SHB region as in the lower figure in Fig. 1 (b). The iSHB effect would only happen in a very short section of EDF. However, if forcing part of the EDF section to work in the iSHB region by turning off the pump power (or by making the pump power be very low), while on the other hand enhancing the pumping in the rest of the EDF section so as to keep the overall averaged inversion level (equivalent to the final gain level) unchanged, the overall SHB magnitude can be reduced. In the following, we validate this idea by experiments.

Firstly, we test the case of one single signal wavelegnth (1532 nm). A single stage amplifier using 1 meter of L1500 EDF and forward 976 nm pumping is built, see Fig. 2 (a). The light source contains a saturation tone fixed at 1532 nm (the signal) and another tunable laser with power of < -35 dBm (the probe). The EDF is divided into two sections, each 0.5 m. In-between the two EDF sections, two WDM couplers are inserted. The common ports of the WDM couplers are spliced with the EDFs. Their signal and pump ports are spliced to each other. Both the residual signal and pump of the first EDF will be injected into the second EDF, experiencing a slight insertion loss. This architechture corresponds to the situation of "w/o SHB compensation". For introducing SHB compensation, what needs to be done is to break the splice joint of the WDM couplers' pump ports and dump the residual pump power from the first EDF. The second EDF will then be forced into being un-pumped (iSHB region). The pump power injected into the first EDF will need to be increased accordingly so as to bring N_2 back to its original level. Fig. 2 (b) plots the SHB spectra ΔG which are the difference between the inhomogeneous and the homogeneous gain profiles under a fixed value of N_2 (estimated to be ~0.62 in this specific case). As predicted by the theory, the measured ΔG is significantly reduced at almost all the probe wavelengths (the blue curve). Fig. 2 (c) summaries the SHB depths measured under different values of N_2, before and after compensation. The SHB compensation is remarkably effective. Due to the limit of the available pump power, N_2 values with compensation is restricted between 0.5 ~ 0.65.

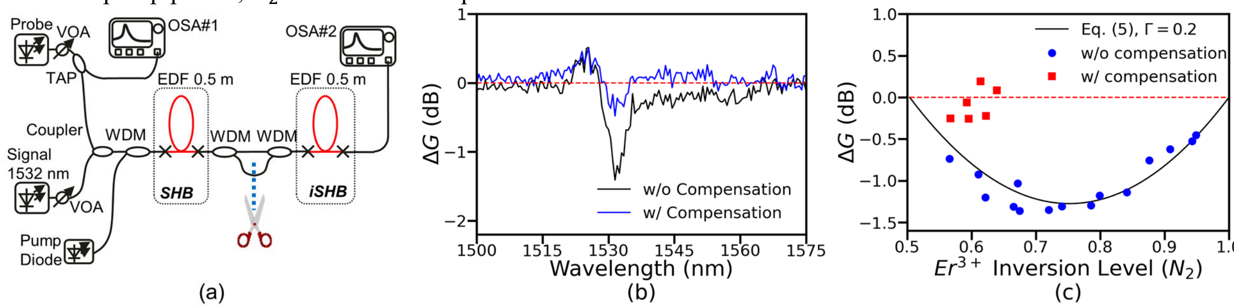

Fig. 2. Experimental validation of the SHB self-compensation under the condition of single signal wavelength (1532 nm). (a) The experimental setup; (b) the SHB spectra before (black) and after (blue) compensation; (c) a summary of the SHB depths at 1532 nm, before (blue dots) and after (red rectangles), under different Er^{3+} inversion levels.

Secondly, we replaced the signal source by a reconfigurable comb-like ASE source, see Fig. 3 (a). The ASE source contains 60 channels with 150 GHz spacing, covering a wavelength range from 1524 to 1572 nm (*super C-band*). Each channel is made to be the "signal" when its power is set to ~ -15 dBm (~ 0.28 dBm for 60 channels) while it becomes the "probe" when being attenuated to ~ -40 dBm. Two optical spectrum analyzers (OSAs) are used to monitor the input and output spectra simultaneously so as to calculate the gain. The length of the EDF is increased to in-total 4 meters in order to get an overall target gain of ~14 dB. The gain flattening filter is implemented offline. Fig. 3 (b) and (c) show the gain spectra before and after compensation respectively, under three partial-loading cases. We can see that the amplifier becomes a "stiffer" one. Not only the signal gain distribution but also the entire probe gain profile become much more uniform after compensation. The cost of this method is that around × 2 pump power is needed for the compensation. However, the SHB induced gain deformation mainly happens under the partial-loading cases where the input signal power is low, so the required pump power will also be low. The compensation can be triggered only when the partial-loading case happens. After all, it doesn't require any additional pump diode.

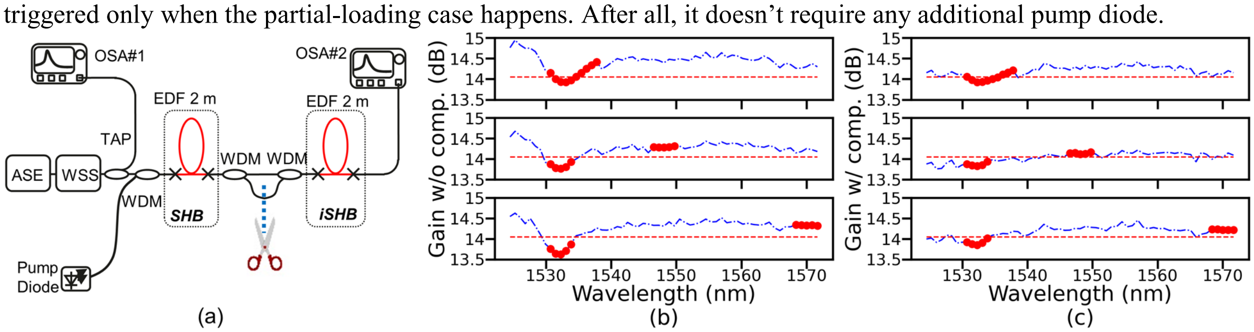

Fig. 3. Experimental validation of the SHB self-compensation under the condition of multiple signal wavelengths. (a) the experimental setup; (b) the gain spectra before compensation, where the red dots are the signal gain and the blue curves are the gain profile detected by low-power probe signals; (c) the gain spectra after compensation.

3. Conclusion

We demonstrate theoretically and experimentally: 1) the EDF's SHB magnitude is generally a parabolic function of the Er^{3+} inversion level; 2) the sign of the SHB induced gain deformation can be controlled by managing the pump power; 3) by forcing two EDF sections to have opposite signs of SHB, the overall SHB can be suppressed.

4. References

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