Research Article | Vol. 25, No. 26 | 25 Dec 2017 | OPTICS EXPRESS 32451
Optics EXPRESS

Bistability in a ring erbium-doped fiber laser due to ejected backward amplified spontaneous emission

MICHAEL ZHURAHOV, ALEXANDER BEKKER, BORIS LEVIT, RAFI WEILL, AND BARUCH FISCHER*

Department of Electrical Engineering, Technion, Haifa 32000, Israel
**fischer@ee.technion.ac.il*

Abstract: We show and identify the role of the backward amplified spontaneous emission (ASE) in inducing bistability and hysteresis in a unidirectional ring erbium-doped fiber (edf) laser. It results from the interplay between the signal and the backward ASE in the gain medium that is ejected from the fiber loop by an isolator. A removal of the isolator eliminates the bistability. Another important factor is the strong wavelength dependence of the absorption and emission coefficients and their ratio.

OCIS codes: (190.1450) Bistability; (190.4370) Nonlinear optics, fibers; (140.3500) Lasers, erbium.

References and links

1. H. M. Gibbs, S. L. McCall, and T. N. C. Venkatesan, "Differential gain and bistability using a sodium-filled Fabry-Perot interferometer," Phys. Rev. Lett. **36**, 1135–1138 (1976).
2. H. M. Gibbs, S. L. McCall, T. N. C. Venkatesan, A. C. Gossard, A. Passner, and W. Wiegmann, "Optical bistability in semiconductors," Appl. Phys. Lett. **35**, 451–453 (1979).
3. H. M. Gibbs, *Optical Bistability: Controlling Light with Light* (Academic, Orlando, 1985).
4. A. Szoke, V. Daneu, J. Goldhar, and N. A. Kurnit, "Bistable optical element and its applications," Appl. Phys. Lett. **15**, 376 (1969).
5. V. R. Almeida and M. Lipson, "Optical bistability on a silicon chip," Opt. Lett. **29**(20), 2387–2389 (2004).
6. A. Baas, J. Ph. Karr, H. Eleuch, and E. Giacobino, "Optical bistability in semiconductor microcavities," Phys. Rev. A **69**, 023809 (2004).
7. J. Shao, S. Li, Q. Shen, Z. Wu, Z. Cao, and J. Gu, "Experiment and theoretical explanation of optical bistability in a single erbium-doped fiber ring laser," Opt. Express **15**(7), 3673–3679 (2007).
8. J. M. Oh and D. Lee, "Strong optical bistability in a simple L-band tunable erbium-doped fiber ring laser," IEEE J. Quantum Electron. **40**, 374–377 (2004).
9. P. C. Becker, N. A. Olsson, and J. R. Simpson, *Erbium Doped Fiber Amplifiers: Fundamentals and Technology* (Academic, 1999).
10. E. Desurvire, *Erbium-Doped Fiber Amplifiers* (Wiley, 1994).
11. R. Weill, A. Bekker, B. Levit, M. Zhurahov, and B. Fischer, "Thermalization of one-dimensional photon gas and thermal lasers in erbium-doped fibers," Opt. Express **25**(16), 18963–18973 (2017).
12. D. E. McCumber, "Theory of phonon terminated optical masers," Phys. Rev. **134**, 299 (1964).
13. R. M. Martin and R. S. Quimby, "Experimental evidence of the validity of the McCumber theory relating emission and absorption for rare-earth glasses," J. Opt. Soc. Am. B **23**(9), 1770 (2006).
14. E. H. Kennard, "On the Interaction of Radiation with Matter and on Fluorescent Exciting Power," Phys. Rev. **28**, 672 (1926).
15. B. I. Stepanov, "A universal relation between the absorption and luminescence spectra of complex molecules," Dokl. Akad. Nauk SSR **112**, 839 (1957).

1. Introduction

Optical bistability and hysteresis have been demonstrated in various systems and mechanisms [1–8]. In most cases it was observed in Fabry-Perot (FP) etalons with nonlinear dispersive or absorptive media, where an interplay between the FP resonance frequency, beam intensities and reflections results in bistability.

Our research is done in simple unidirectional ring erbium-doped fiber (edf) lasers where we observed bistability and hysteresis different from the usual above mentioned mechanisms and systems. We find in the experiment, verified by a theoretical analysis, that the backward

#307873 https://doi.org/10.1364/OE.25.032451
Journal © 2017 Received 25 Sep 2017; revised 8 Dec 2017; accepted 8 Dec 2017; published 13 Dec 2017

ASE light in the edf amplifier has a crucial role in inducing the bistability when it is ejected out of the cavity by an isolator. In the analysis we use the rate equations for the three-level erbium-doped fiber gain media [9–11] and solve them numerically. We add that bistability was observed in ring edf lasers [7,8], and the backward ASE was seen to exist and influence the laser behavior [8]. Nevertheless, it was not reported and identified that the backward ASE is solely responsible for the bistabilty.

The simple system that shows bistability is schematically shown in Fig. 1(a) but its origin was unclear. The way to identify that it resulted from the backward ASE was by splitting the 20*m* edf to two sections, a main one of 15*m* that was pumped and a small part of 5*m* placed before the WDM pumping coupler, and thus is non-pumped directly, as is schematically shown in Fig. 1(b). We then examined the laser system with and without an additional isolator between the two edf sections. As described below, the bistability continued to be present when we included the second isolator, as shown in Fig. 2, but it disappeared without it, as shown in Fig. 3. The bistability is therefore caused by the isolator, the first one (Isolator 1) in Fig. 1(a) and the second one (Isolator 2) in Fig. 1(b), that ejected the backward ASE out of the laser loop, in a similar way to the role of the reflection loss in a bistable nonlinear FP. The interplay of the backward ASE and the forward propagating signal that both compete for gain in the amplifier, when the first one is ejected and lost, induces a resistance to switching, hysteresis and bistability. Another important factor that is accounted for in the analysis below, is the strong wavelength dependence of the absorption and emission coefficients $\sigma_{12}(\lambda)$ and $\sigma_{21}(\lambda)$, and their ratio, as shown in Fig. 4. While the peaks of the coefficients are near 1530*nm*, their ratio peaks at a longer wavelength region of ~(1600-1620)*nm,* as seen in Fig. 4(b), where the lasing occurs [11]. It adds to the gain-absorption, saturation and loss variations before and at lasing, enhancing the resistance to switching from a non-lasing state dominated by the ASE light and the signal circulating in the ring when lasing starts at a higher wavelength. We note on the temperature dependent emission-absorption coefficients ratio shown in Fig. 4(b) that follows the McCumber [12,13] or Kennard-Stepanov [14,15] relation $\sigma_{12}(\nu)/\sigma_{21}(\nu) \propto e^{\beta h\nu}$, where $\beta = 1/k_B T$, T is temperature, h and k_B are the Planck and Boltzmann constants, ν and λ are frequency and wavelength. The almost straight line semi-log slope in Fig. 4(b) fits the thermal value for $T = 300K$ [11]. A similar thermal lasing at ~1605*nm* was shown in our former work with such lasers [11].

2. Experimental setup and results

Schematics of two laser systems are shown in Figs. 1(a) and 1(b). They both consist of edf fibers with a core absorption of ~30*dB/m* at 1530*nm*, isolator(s), a 980*nm* CW diode laser pump, a wavelength division multiplexer (WDM) to combine the pumping light with the signal that circulates in the laser, and an output coupler. The experiments were done at a room temperature. In the first system shown in Fig. 1(a) we have one section of 20*m* edf, and in the second one the edf is split and a 5*m* section is placed before the pumping WDM, and in addition a second isolator (Isolator 2) is placed between the two sections. Then only the 15*m* section is directly pumped. The first system produced bistability and hysteresis and so the second one with the additional isolator. Nevertheless, when this isolator is removed the bisatability is eliminated.

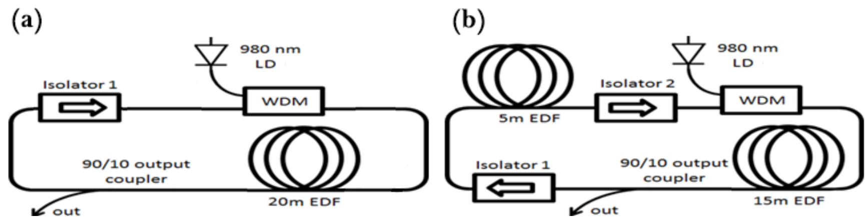

Fig. 1. Schematics of (a) the basic edf laser system, and (b) the experimental laser system with two edf sections and a second isolator.

We describe the behavior of the system of Fig. 1(b) that shows bistability like the system in Fig. 1(a). The purpose of Isolator 1 is to eliminate a backwards propagating signal, whereas Isolator 2 is used to test the role of the backwards propagating ASE. We have in Fig. 1(b) two sections of edf, of $15m$ and $5m$, but only the long one is directly pumped. We can see in the experimental results with Isolator 2 in Fig. 2 the broad bistability region, ranging from $232mW$ to $363mW$ of the pump power. The $5m$ edf section adds to the $15m$ part providing a saturable gain-absorption system. When the pumping increases lasing starts when there is enough gain in the long edf section to overcome the losses, while affecting the two satuarable sections, lowering the gain and the absorption. Here the backwards ASE is strongly absorbed prior to lasing in the $5m$ edf section, but it remains in the cavity. As said above, the situation is different when Isolator 2 is present where the backward ASE is ejected out of the cavity. Before lasing it grows with pumping in the gain section but doesn't contribute to the bleaching and to lowering the absorption of the non-pumped $5m$ edf section. Nevertheless, a further increase of the pump power switches on the lasing at a higher than the former lasing starting point. Then the forward signal also starts to bleach the absorption with much less effect of the backward ASE. The opposite way of lowering the pump power from the lasing state gives a lower balanced gain-loss point, due to the saturation of the non-pumped edf and the long lasing wavelength with less absorption, that keeps the lasing until it stops at a point that is below the switch-on point.

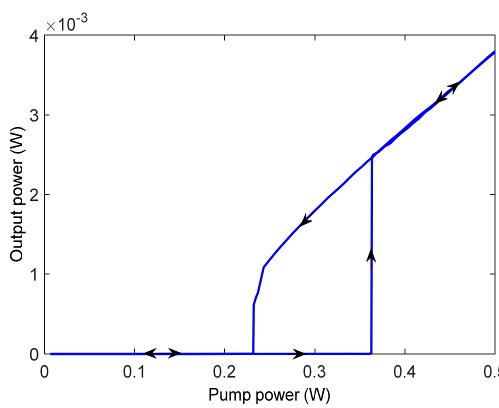

Fig. 2. Experimental output power as a function of pump power, showing the bistability. The arrows show the pump increase or decrease directions.

Figure 2 shows a very broad hysteresis region for the system of Fig. 1(b) with Isolator 2. We emphasize that most of the lasing power is at a wavelength of $1605nm$ (where the ratio of the emission and absorption coefficients is the largest.) The switching on point occurs with a discontinuous jump in the signal power. In our system it occurred at a pumping of $363mW$. The lasing switching off was at a pump power of $232mW$ where the signal dropped discontinuously to a close to zero value. We had a $131mW$ wide bistablity range. When we removed Isolator 2 from our system, the hysteresis was almost absent, as is seen in Fig. 3,

Optics EXPRESS

leaving a hysteresis range of about ~4mW, less than 2% of the original width with Isolator 2. We think that this very small remaining hysteresis is due to the losses in the WDM coupler placed between the two edf sections.

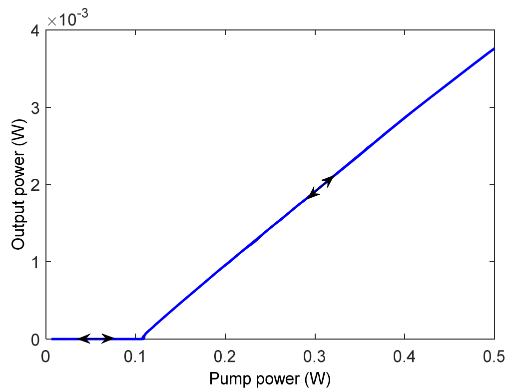

Fig. 3. Experimental output power as a function of pump power when isolator 2 is removed. The bistability region is nearly absent. The arrows show the pump increase or decrease directions.

3. Theoretical analysis

The analysis of the laser system is based on the rate equations of three-level media for multiple wavelengths [9–11], assuming that electrons in the third level drop to the second one instantly, and the lasing transition occurs between two broad levels with an overall population density in each of them of N_1 and N_2, and a total erbium population density of $N_d = N_1 + N_2$:

$$\frac{dP_p(z)}{dz} = -\sigma_p N_1(z), \quad P_{s,total}(\nu,z) = P_{s,backward}(\nu,z) + P_{s,forward}(\nu,z), \quad N_1(z) + N_2(z) = N_d \tag{1}$$

$$\frac{dP_{s,foward}(\nu,z)}{dz} = \left(\sigma_{21}(\nu)N_2(z) - \sigma_{12}(\nu)N_1(z)\right)P_{s,foward}(\nu,z) + kN_2(z)\sigma_{21}(\nu)g(\nu)h\nu \tag{2}$$

$$-\frac{dP_{s,backward}(\nu,z)}{dz} = \left(\sigma_{21}(\nu)N_2(z) - \sigma_{12}(\nu)N_1(z)\right)P_{s,backward}(\nu,z) + \kappa N_2(z)\sigma_{21}(\nu)g(\nu)h\nu \tag{3}$$

$$\frac{dN_2(z)}{dt} = \sigma_p N_1(z)\frac{P_p(z)}{h\nu_p A_p} + \int d\nu \sigma_{12}(\nu)N_1(z)\frac{P_s(\nu,z)}{h\nu A_s} - \int d\nu \sigma_{21}(\nu)N_2(z)\frac{P_s(\nu,z)}{h\nu A_s} - \frac{N_2(z)}{\tau_{sp}} = 0 \tag{4}$$

P_p, $P_{s,foward}$ and $P_{s,backward}$ are the pump, forward and backwards signal powers. The other quantities are: The spontaneous time for the transition from level 2 to 1 is $t_{sp} \approx 10^{-2} s$, the effective fiber core area for the pump and signals $A_p, A_s \approx 24\mu m^2$, and $\sigma_p \approx 2.6\times 10^{-25}\ m^2$, used the values in Fig. 4(a) for σ_{12} and σ_{21}, $v_p = 3\times 10^{14} / s$, and $N_d = 9.8\times 10^{24} / m^3$. We solved the equations numerically, as was done in a previous paper [11], and obtained the theoretical figures.

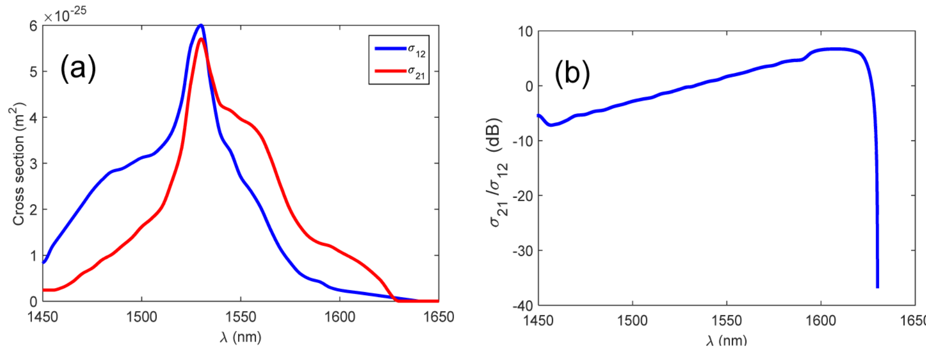

Fig. 4. (a) Emission (red), and absorption (blue) spectra for erbium. (b) Emission-absorption ratio as a function of wavelength.

Figure 4(a) shows the emission and absorption coefficients that depend on the wavelength. The ratio between these coefficients that also depends on the wavelength is shown in Fig. 4(b). It follows the McCumber relation [11–13] increasing exponentially until it peaks at 1605*nm* where lasing occurs. Therefore, besides the saturation effect due to the backward ASE and the forward lasing that lowers its absorption in the non-pumped edf, there is a further decrease in the losses at the lasing since it occurs at the high wavelength region. As can be seen in in Fig. 5, we obtain a broad hysteresis range, agreeing with the experimental results. We can also see that once the system starts to lase, the output power can be approximated by $P_{output} \approx P_{pump} \cdot (980/1605) - constant$, as the behavior of common lasers with the addition of a large bistablity region.

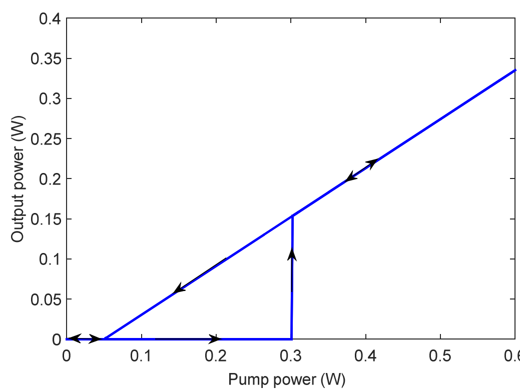

Fig. 5. Theoretical output power as a function of pump power. The pump power is normalized by the 980/1605 wavelength ratio.

The bistabilty is similar to that in FP with a saturable-absorber [4], where the reflection loss adds to the saturable-absorber, providing hysteresis. In our case it is the backward ASE loss due to the isolator that is larger when the power in the ring is low compared to the state where the lasing starts, as can be seen in Fig. 6. It adds to the resistance to the switching from non-lasing to lasing state and vice versa, where different thresholds have to be reached to switch between the two states.

Optics EXPRESS

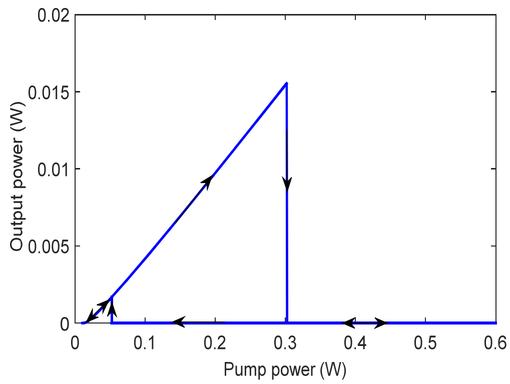

Fig. 6. Backwards ASE power as a function of the pump power. The bistability region is exactly the same as that of the output power.

When we remove Isolator 2 from this system of Fig. 1(b), the backwards ASE remains in the cavity but is mostly absorbed by the non-pumped 5*m* edf, that becomes saturated. It then lowers the absorption of the forward propagating signal that is amplified by the 15*m* gain section, that at some point is large enough to provide lasing, as can be seen in Fig. 7. Without that loss of the backward ASE by the isolator the system becomes continuous and the hysteresis is eliminated.

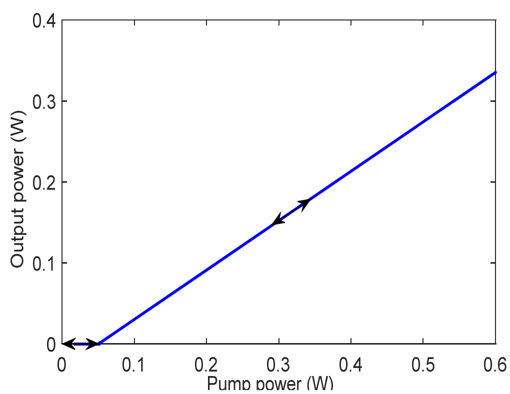

Fig. 7. Theoretical results for the output power as a function of pump power when Isolator 2 is removed.

5. Conclusions

We have shown and studied a bistabilty and hysteresis phenomenon in a simple ring laser. We have found that the backwards ASE that is stopped and ejected by an isolator induces resistance to the switching to and from the lasing state. We also discussed the enhancement effect of the strong wavelength dependence of the emission and absorption coefficients prior and at lasing.

Funding

Pazy Foundation; Israel Science Foundation (ISF).