Highly Yb^{3+}/Er^{3+}-codoped microring resonator performance in migration-assisted upconversion regime

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***Abstract*—The amplifying and filtering performance of a highly Yb/Er-codoped add-drop filter is analyzed and discussed. The use of the microscopic statistical formalism to describe energy-transfer inter-atomic mechanisms allows determining realistic optimum parameters and working conditions.**

Keywords-optical microring resonator; Yb^{3+}/Er^{3+}-codoping; energy-transfer inter-atomic mechanisms; optimized design.

I. INTRODUCTION

Optical microring resonators are attracting much interest due to their potentiality as fundamental building blocks for a large variety of applications in photonic circuits, including channel dropping filters [1], add/drop (de)multiplexers [2], modulators [3], switches [4], sensors [5] and lasers [6].

The basic structure under analysis (commonly termed an add-drop filter) consists of a microring resonator side-coupled to two straight waveguides for signal input/output. When the structure host material is Yb/Er-codoped the device may exhibit both filtering and amplifying functionalities. However, the required high doping levels enhance efficiency-limiting energy transfer inter-atomic interactions, which have to be considered for an optimized design. Unrealistically, the optimization studies available have ignored these mechanisms in their models [7]. A precise formalism for the effect of both upconversion and migration is the microscopic statistical formalism (MSF) based on the statistical average of the excitation probability of the Er^{3+} ion in a microscopic level [8]. This formalism was recently adapted to include Yb^{3+}-sensitization and transversally resolved rate equations, which become essential due to the nonlinear character of the energy transfer mechanisms [9].

II. ACTIVE MICRORING RESONATOR TRANSFER FUNCTIONS.

A scheme of the structure is shown in Figure 1. R is the radius of the microring, $2L = 15000\,\mu m$ is the total length of the upper and lower waveguides, L being the length between the waveguide ports and the coupling point. We assume that the microring and the waveguides have the same mode propagation constant, β, amplitude loss coefficient, α, and gain coefficient, g.

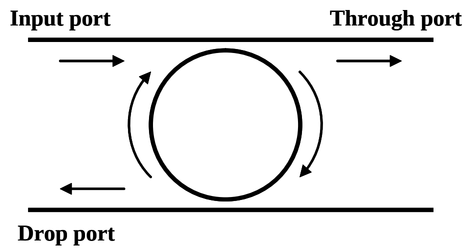

Figure 1. Scheme of the structure: a microring resonator side-coupled to two straight waveguides for signal input/output.

Then, the common complex propagation constant is $\beta - j\alpha + jg$. Let κ_i (i=1,2) be the amplitude coupling ratio between the microring and the upper and lower waveguides, t_i be the corresponding transmission ratio, which satisfies $\kappa_i^2 + t_i^2 = 1$. Then, the transfer functions from the input port to the through and drop ports are [7]:

$$|T|^2 = \left| \frac{\left[t_1 - t_2\, exp(-j2\varphi) \right] exp(-j2\psi)}{1 - t_1 t_2\, exp(-j2\varphi)} \right|^2 \quad (1)$$

$$|D|^2 = \left| \frac{\kappa_1 \kappa_2\, exp\left[-j(\varphi + 2\psi) \right]}{1 - t_1 t_2\, exp(-j2\varphi)} \right|^2 , \quad (2)$$

respectively, where:

$$\varphi = \pi R(\beta - j\alpha + jg) \quad \text{and} \quad \psi = L(\beta - j\alpha + jg) . \quad (3)$$

If $g > 0$ in (3) the device is a microring resonator amplifier and the fulfillment of the resonance condition depends also on the gain coefficient g what forces a previous optimizing design based on the expected working conditions.

III. RESULTS AND DISCUSSION

We determine the value of the gain coefficient by calculating it in an Yb/Er-codoped straight waveguide amplifier [7]. We assume the core and cladding indexes and the core dimensions in [10] and the Yb/Er-codoped phosphate glass spectroscopic parameters in [9]. Once the effective indexes are calculated the radius of the microring, $R = 16.4\,\mu m$, is selected not only to match the resonance condition for pump and signal (the resonant orders of the pump and signal are $m_p = 161$ and $m_s = 102$) but also to keep the radiation loss as low as possible. In our case, the power bend loss coefficient is small enough compared to the assumed power transmission loss coefficient, $2\alpha = 0.5\,dB/cm$, to be neglected. We assume as pump and signal input powers 250 mW and 1 µW, respectively, and their wavelengths are $\lambda_p = 976\,nm$ and $\lambda_s = 1534\,nm$. In order to determine the signal gain coefficient, the transversally-resolved MSF is used to accurately describe the energy-transfer mechanisms contribution in the rate equations. In Fig. 2 the signal gain is plotted as a function of Yb^{3+}-ion concentration for five Er concentrations. The maximum gain, 9.84 dB, is achieved for $N_{Yb} = 1x10^{27}\,m^{-3}$ and $N_{Er} = 4\,x10^{26}\,m^{-3}$, more realistic values than those reported in [7]. Once g is determined, an optimum coupling ratio $\kappa_1 = \kappa_2 = 0.085$ (and subsequently the central coupling gap [11]) can be calculated.

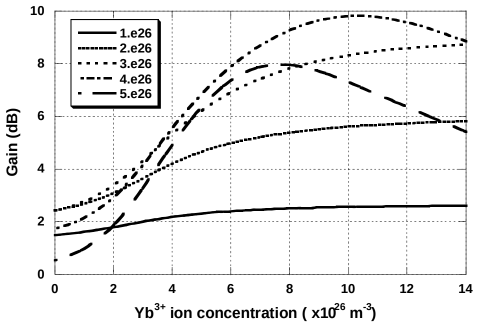

Figure 2. Straight waveguide amplifier gain as a function of Yb^{3+}-ion concentration for five Er concentrations.

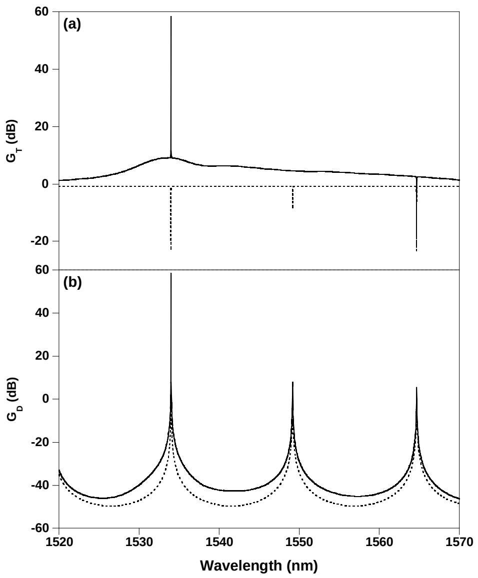

Figure 3. Output spectra of the (a) through and (b) drop ports of the passive (dotted line) and active (solid line) microring structures in the 1.53 nm gain band.

Finally, from the values of through and drop coefficients in (1) and (2) the output power gain spectra are defined as:

$$G_T(dB) = 10\log_{10}\left(|T|^2\right) \text{ and } G_D(dB) = 10\log_{10}\left(|D|^2\right) \quad (4)$$

In the output spectra in Fig. 3 it can be noticed how, if $g = 0$, the device shows a typical filtering behaviour. However, if $g > 0$ in the through port spectrum the device exhibits only the amplifying function whereas in the drop port both functions, amplifying (near the signal resonant wavelength) and filtering (far from the signal resonant wavelength) can be found. The achievable signal power gain reaches 58.3 dB.

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REFERENCES

[1] H. Okamoto, M. Haraguchi and T. Okamoto, "Filtering characteristic of a microring resonator with a gap," Electronics and Communications in Japan Part II-Electronics, vol. 89(5), pp. 25-32, 2006.

[2] B. E. Little, S. T. Chu, P. P. Absil et al., "Very high-order microring resonator filters for WDM applications," IEEE Phot. Technol. Lett, vol. 16(10), pp. 2263-5, 2004.

[3] M. Balakrishnan, M. Faccini, M. B. J. Diemeer et al. "Microring resonator based modulator made by direct photodefinition of an electro-optic polymer," Applied Physics Letters, vol. 92(15), pp.153310, 2008.

[4] M. Foerst, J. Niehusmann, T. Plotzing et al. "High-speed all-optical switching in ion-implanted silicon-on-insulator microring resonators," Optics Letters, vol. 32(14), pp. 2046-8, 2007.

[5] D. X. Dai, S. L. He, "Highly-sensitive sensor with large measurement range realized with two cascaded microring resonators," Optics Communications, vol. 279 (1), pp. 89-93, 2007.

[6] J. Wang, K. Y. Wong, "Polarization characteristics of a light-emmiting polymer microring laser," Applied Physics B-Lasers and Optics, vol. 87(4), pp. 685-91, 2008.

[7] Y. H. Wang, C. S.Ma, X. Yan, D. M. Zhang, "Analysis for amplifying characteristics of Er^{3+}-Yb^{3+}-co-doped microring resonators," Optics & Laser technology, vol. 42, pp. 336-340, 2010.

[8] D. Khoptyar, S. Sergeyev and B. Jaskorzynska, "Homogeneous upconversion in Er-doped fibres under steady state excitation. Analytical model and its Monte-Carlo verification" J. Opt. Soc. Am. B , vol. 22(3), pp. 582-590, 2005.

[9] J. A. Vallés, "Method for accurate gain calculation of a highly Yb^{3+}/Er^{3+}-codoped waveguide amplifier in migration-assisted upconversion regime," *IEEE J. Quantum Electron*., vol. 47(8), pp. 1151-1158, 2011.

[10] Y. H. Wang, C. S. Ma, D. L. Li and D. M. Zhang, "Formulized analytical technique for gain characteristics of phosphate glass Er^{3+}/Yb^{3+} co-doped waveguide amplifiers," Optica Applicata, vol. 38(2), pp. 329-339, 2008.

[11] C. S. Ma, X. Yan, Y. Z. Xu et al. "Characteristic analysis of bending coupling between two optical waveguides," Optical and Quantum Electronics vol. 37(11), 1055-67, 2005.