Theoretical and experimental study of erbium doped photonic crystal fiber ring laser

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Abstract - **Results of theoretical and experimental studies of a photonic crystal fiber erbium doped ring laser are presented. Modeling parameters have been measured directly or calculated for the photonic crystal fiber analyzed. The simulations were carried out by solving in a self consistent manner the propagation and rate equations.**

I. INTRODUCTION

Erbium doped fiber amplifiers (EDFA) and lasers (EDFL) are crucial devices in the area of optical fiber telecommunications. Using photonic crystal fiber (PCF) can improve the basic parameters of EDFA and EDFL. One advantage of PCF technology is the large flexibility in the shaping of waves (modes) supported by the photonic crystal structure. Due to these properties higher values of the overlap integral between the pump and the signal can be obtained. This allows high efficiency fiber laser and amplifiers to be designed, [1,2]. The erbium doped fiber ring laser (EDFRL) is the most popular type of the erbium doped fiber laser configuration. EDFRL has a relatively simple construction whereby the output signal is fed up to the input. However, in the literature there are only a few publications that consider ring laser modeling, [3, 4]. In this paper the behavior of the EDPFRL is analyzed using a numerical model that is based on iterative solution of the rate equations, propagation equations for pump and signal and appropriate boundary conditions. Parameters used in the simulation were measured for a PC fiber developed in our laboratories. Experimental results for the EDPFRL constructed are also presented.

II. RING LASER

The structure of the ring laser realized is presented in Figure 1. The ring configuration has several advantages. The first of them is the relatively simple construction; because the output signal is fed back to the input no mirrors are required. The ring configuration is also very flexible because elements that can change the laser characteristics (e.g. filters, modulators) can be easily added to the laser cavity, [3]. The basic ring laser contains a wavelength division multiplexer (WDM) that combines the pump with the laser signal. Another key component is the output coupler that provides the laser signal. Other elements that can be used in ring configuration include an isolator that protects the pump diode from back reflection and provides unidirectional propagation, and a polarization controller that sets the polarization state of the wave in cavity.

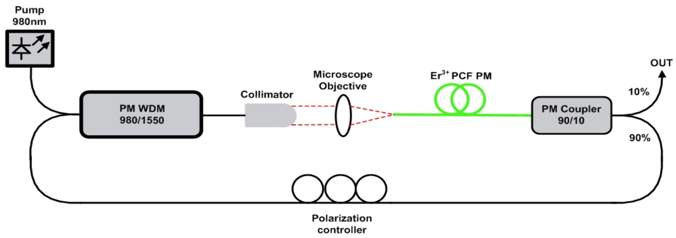

Fig.1 Configuration of the erbium doped ring laser

III. NUMERICAL MODELING

The ring laser performance was analyzed by solving the level population rate and optical propagation equations. A two level population model of Er^{3+} is assumed. The population of each level can be described by a nonlinear differential equation:

$$\frac{dN_2}{dt} = N_1(W_{pa} + W_{sa}) - N_2(W_{pe} + W_{se} + W_{21}) \quad (1)$$

$$\frac{dN_1}{dt} = -N_1(W_{pa} + W_{sa}) + N_2(W_{pe} + W_{se} + W_{21}) \quad (2)$$

.

Propagation of pump and signal power along the active fiber is described by the following differential equations:

$$\frac{dP_p}{dz} = (N_2\sigma_{pe} - N_1\sigma_{pa})\Gamma_p P_p - \alpha P_p \quad (3)$$

$$\frac{dP_s^{\pm}}{dz} = \pm(N_2\sigma_{se} - N_1\sigma_{sa})\Gamma_s P_s^{\pm} \pm \alpha P_s^{\pm} \quad (4)$$

Boundary conditions used for ring laser simulations are:

$$P_s^n(z = 0^+) = P_s^{n-1}(z = L^+)\cdot(1 - R_{out})\alpha_{ring} \quad (5)$$

$$P_s^n(z = L^-) = P_s^{n-1}(z = 0^-)\cdot(1 - R_{out})\alpha_{ring} \quad (6)$$

$$P_p(z = 0^+) = \beta \cdot P_p + P_p(L^+) \quad (7)$$

where n denotes the iteration number , α_{ring} is the cavity loss, R_{out} is the coupling ratio of the output coupler, β is the

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coupling ratio of the WDM coupler. In the simulations we guess the signal at a given position along the fiber and use it as an initial value. Then we propagate the signal in the ring. Once the full round trip is completed we compare the calculated signal with the initial guess. If the difference is larger than the assumed tolerance the process is repeated until convergence is achieved. This simple and robust algorithm proved stable in all cases considered.

IV. RESULTS

The PCF structure that was manufactured and modeled in this paper is presented in Fig.2. The basic parameters used in the modeling were either measured in our laboratories or calculated. The waveguide parameters of the manufactured structure are $\Lambda = 4.3$ (pitch) and the filling factor $d/\Lambda = 0.48$. The calculated value of birefringence at 1530 nm is equal to $6.6 \cdot 10^{-4}$. The measured numerical aperture of the fiber is NA=0.26 at 1530 nm. The measured parameters connected with Er dopants are the emission cross section $\sigma_e(\lambda) = 3.2\times10^{-21}\,cm^2$ and the absorption cross section $\sigma_a(\lambda) = 2.94\times10^{-21}\,cm^2$ for the signal at 1550 nm and the absorption cross section $\sigma_a(\lambda) = 1.87\times10^{-21}\,cm^2$ for the pump at 980 nm. The metastable lifetime $\tau_{21} = 10\,ms$ and the erbium concentration is $N = 1\times10^{19}\,ions/cm^3$. The confinement factors for the pump and the signal waves were calculated using a vectorial mode solver [5].

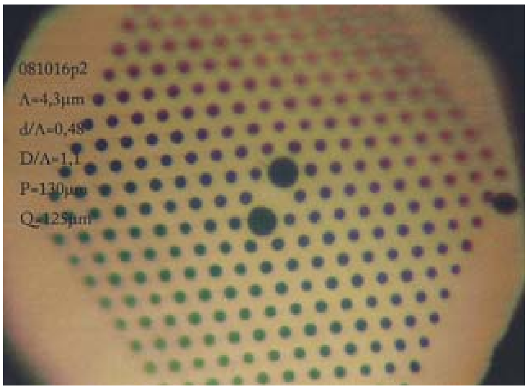

Fig. 2. Cross-section of the active photonic fiber

Fig.3 shows the calculated dependence of laser efficiency on losses in the ring cavity. The slope efficiency for 1 dB losses in the ring cavity was equal to 45% but when the losses are at the level of 9 dB the slope efficiency is only 6.9%. The experimental ring laser suffered particularly from a large field mismatch between the active photonic fiber and the passive traditional fiber. It was therefore important to select the optimal value for the fiber length. Fig.4 shows the dependence of the output power on the fiber length. This figure confirms that using a fiber that is too long results in an unnecessary increase of the laser losses. Further, the optimal selection of the fiber length depends on the pump power coupled into the fiber. Finally, we would like to comment that in spite of the low efficiency the realised laser shows stable single wavelength operation and a 38 dB signal-to-noise ratio.

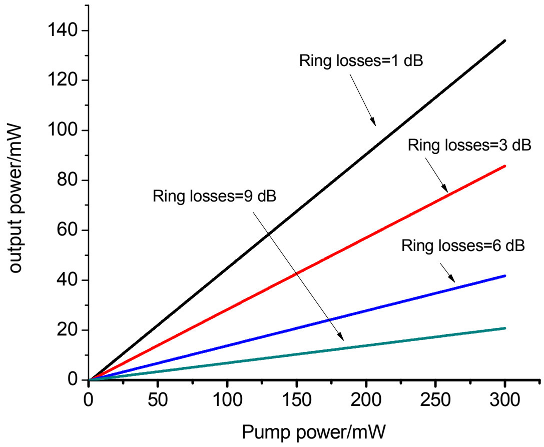

Fig.3 Calculated dependence of the output power on the pump power for selected values of ring cavity losses L=10m, $\lambda_s = 1530\ nm$,R_{out}=90%.

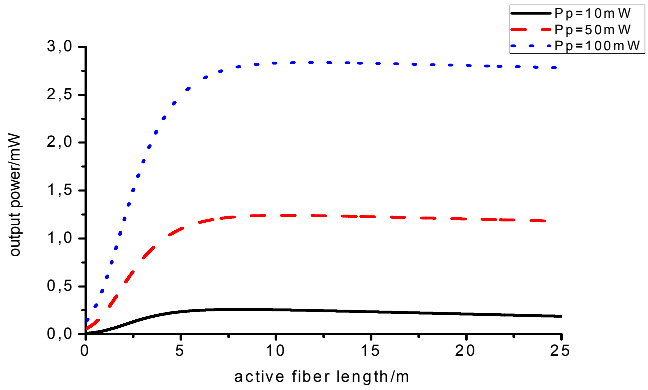

Fig.4 Calculated output power versus active fiber length: $\lambda_s = 1530\ nm$, $\alpha_{ring} = 10\ dB$,R_{out}=50%.

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