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Highly Optimized Tunable Er³⁺-Doped Single Longitudinal Mode Fiber Ring Laser, Experiment and Model

Christian Vestergaard Poulsen and Milan Sejka

Abstract—A CW tunable diode-pumped Er³⁺-doped fiber ring laser, pumped by diode laser at wavelengths around 1480 nm, is investigated. Wavelength tuning range of 42 nm, maximum slope efficiency of 48% and output power of 14.4 mW have been achieved. Single longitudinal mode lasing with a linewidth of 6 kHz have been measured. A fast model of erbium-doped fiber laser is developed and used to optimise output parameters of the laser.

INTRODUCTION

IN recent years [1]–[5], there has been an increased interest in tunable fiber ring resonators, employing Er³⁺-doped fibers. Ring configurations allows mirror free operation and total integration of components, thus making these lasers attractive for coherent communication, optical fiber sensors, and spectroscopy. So far several experimental results have been obtained with laser diode pumped erbium doped fiber ring configurations. Output power of 4.2 mW, a tuning range of 61 nm, a threshold of absorbed pump power of 2.9 mW, a slope efficiency of 15% [2], and a linewidth of 1.4 kHz [5] have been achieved.

To fully understand the behavior of the erbium-doped fiber laser, it is important to have a theoretical model. We developed a simplified and fast model, based on a theoretical treatment [6]–[9].

Our laser has been designed so as to verify this simple model and to use model predictions to optimize output power and slope efficiency of the fiber ring laser.

CONFIGURATION

The fiber laser configuration is shown in Fig. 1. Pump radiation of the diode laser around the wavelength 1.48 μm is coupled to the ring through a low loss and polarization insensitive wavelength division multiplex (WDM) coupler. The optical isolator with insertion loss of 0.55 dB, isolation of 38 dB and return loss better than 62 dB serves a double purpose. Firstly, it protects the pump source

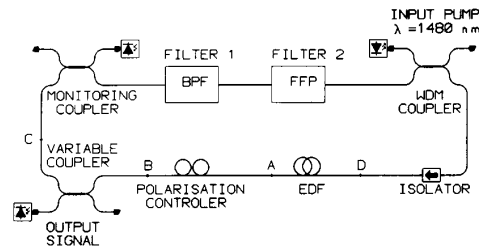


Fig. 1. Experimental configuration of the diode pumped tunable fiber ring laser.

against back reflections and, secondly, it hinders bidirectional lasing in the loop, preventing holeburning in the gain medium. The ring itself consist of 4.0 m of highly doped erbium fiber with a core diameter of 3.5 μm and concentration of erbium ions of $2.1 \times 10^{25} \text{ m}^{-3}$. A polarization controller is used to control the polarization of the propagating light. The signal is coupled from the ring by a variable coupler, allowing us to couple out an optimum amount of the radiation with very low excess loss (0.1–0.2 dB). Two tunable filters are used to enable tuning in a wide wavelength range. The band-pass filter (BPF) has tuning range of 1.52–1.57 μm and bandwidth of ~ 2.5 nm, and the fiber Fabry–Perot (FFP) filter has free spectral range (FSR) of 7.5 GHz and bandwidth of 0.06 nm. Due to a low reproducibility of the variable coupler (hysteresis and offset) a monitor coupler was included for controlling the output coupling ratio x_{out} of the variable coupler. All nonspliced arms of the couplers are angled, assuring higher amplitude and frequency stability of the laser. Overall length of the cavity is 20 m giving a longitudinal mode spacing as narrow as ~ 10 MHz.

MODEL

Our model assume knowledge of material parameters of the used erbium-doped fiber and passive parameters of the ring cavity. It can be used for prediction of the basic laser parameters such as threshold pump power, slope efficiency, tuning range, and output power.

In [8] a simplified model of a single-mode fiber laser was presented by introducing a mean fraction of excited erbium ions along fiber axis, called $\langle x_0 \rangle$. Consequently, the calculations become significantly faster. Compared to a full model, this only gives an error of less than 5%. The

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oscillating wavelength of the laser is given by the filter introduced in the cavity. Assuming that absorbed pump photons may only become amplified spontaneous emission (ASE) photons or signal photons, the output signal power P_s may be found from conservation of the total photon number

$$P_s = \eta_{\text{cav}} \left[P_p \xi (1 - A) - P_{\text{th}} \right] \frac{h\nu_s}{h\nu_p} \quad (1)$$

where P_p is the pump power, P_{th} is the threshold of the pump power, ξ is a factor, taking loss between the pump source and the erbium-doped fiber into account, $h\nu_p$ and $h\nu_s$ are the energies of pump and signal photons, η_{cav} is the cavity efficiency [see (3)] and $1 - A$ is the relative amount of the absorbed pump power evaluated as

$$1 - A = 1 - \exp \left[(\langle x_0 \rangle \sigma_{\text{pe}} - (1 - \langle x_0 \rangle) \sigma_{\text{pa}}) \Gamma_p \rho l \right] \quad (2)$$

where σ_{pe} and σ_{pa} are effective emission and absorption cross sections for the pump, Γ_p is the confinement factor of the pump mode, ρ is the concentration of Er³⁺ ions and l is the length of the ring resonator. The cavity efficiency η_{cav} of the ring resonator may be calculated as

$$\eta_{\text{cav}} = \frac{\eta_{\text{out}} (1 - L_{\text{AB}}) x_{\text{out}}}{1 - (1 - L_{\text{AB}})(1 - L_{\text{CD}})(1 - x_{\text{out}})} \quad (3)$$

where η_{out} represents loss between output coupler and detector, L_{AB} and L_{CD} are relative losses between A and B & C and D in clockwise direction in the configuration and x_{out} is output coupling ratio of the variable coupler. From this expression it appears, that it is important, where the lossy components are placed: the cavity efficiency will be at the largest, when lossy components are placed between C and D .

It may be found from the model, that it is possible to optimize either tuning range, threshold pump power, slope efficiency or output power for each length of the erbium-doped fiber with respect to the output coupling ratio. The variation of the slope efficiency is determined by the variations of the cavity efficiency η_{cav} and the absorption of pump power $1 - A$ (Fig. 2). To optimize slope efficiency (and consequently the output power) of the fiber laser, the output coupling ratio x_{out} is adjusted to 85%. Increase of the output coupling ratio has two effects on the slope efficiency. The cavity efficiency η_{cav} , according to (3), increases and the absorption of pump power decreases due to higher loss in the cavity.

Significantly lower threshold and slightly wider tuning range can be achieved by decreasing the output coupling ratio, but at the expense of lower slope efficiency and output power. Increasing of the output coupling ratio over 90% results in instability of the laser due to high loss.

EXPERIMENT

The maximum output power versus total pump power is measured at 1560 nm (Fig. 3). It gives us maximum output power of 14.4 mW at 43.2 mW of pump power. The

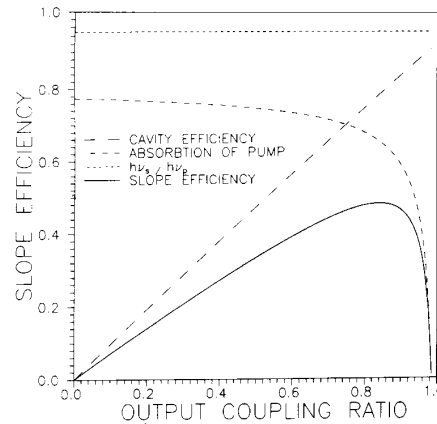


Fig. 2. Slope efficiency as a function of the output coupling ratio at $\lambda_s = 1560$ nm. The length of the erbium-doped fiber is 4 m.

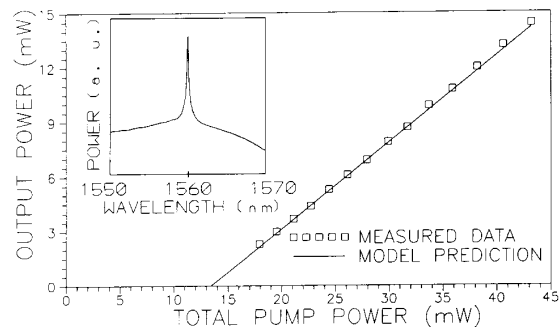


Fig. 3. Output signal power without copropagating pump and ASE versus total pump power. Inset: characteristic power spectrum measured with 0.1 nm resolution.

relatively high threshold (13.4 mW) of the pump power is due to high losses in the components used and loss of pump power between pump source and erbium-doped fiber. Another reason is, that erbium-doped fibers has both absorption and emission of the photons at wavelengths around 1480 nm. This problem can be overcome by pumping at wavelength of 980 nm, but with introducing a decrease of efficiency due to smaller pump photon to signal photon energy rate and excited state absorption of the pump photons. The model prediction shows a very good agreement with the measured data regarding threshold pump power and slope efficiency, where the measured slope efficiency is as high as 48%. Due to fact, that only 70% of the total pump power is absorbed in the erbium-doped fiber, the efficiency, evaluated with respect to absorbed pump power, is 68%. Fig. 4 shows the output power as function of wavelength. Tuning range of the laser within 3 dB decline is 42 nm. The upper limit of the tuning range is caused by the tunability of the band-pass filter. The theoretical curve is in very good agreement with the measured data in respect to tuning range and output power. Humps on the model prediction curve are

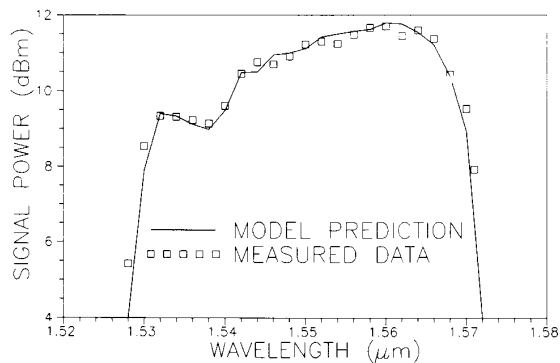


Fig. 4. Output signal power without copropagating pump and ASE versus wavelength.

due to the fact, that absorption and emission cross-section data were available only for discrete values of the wavelength ($\Delta\lambda = 2$ nm). To obtain good agreement between the experimental measurement and model prediction, it is important to precisely determine the wavelength variation of the passive roundtrip loss inside the cavity. An insertion loss of the both filters have been measured in the range of 3–15 dB with higher values at lower wavelengths. The contribution of the fused WDM coupler on overall loss become significant at higher and lower wavelengths due to sinusoidal variation of the insertion loss with minimum at 1552 nm.^{3, 4}

To measure single mode operation of the fiber laser a SuperCavity® Fabry–Perot (SCFP) scanning interferometer with free spectral range of 6 GHz and a finesse of 5000 is used. It gives a resolution of 1.2 MHz, which is sufficient to establish single mode operation in this fiber ring laser where the mode-spacing is ~ 10 MHz. In Fig. 5 a photograph of the whole FSR of the output of the SCFP interferometer is shown (Fig. 5). It demonstrates single mode operation. For measuring the linewidth of the oscillating peak a self-homodyne method with a delay line of 57 km is used, giving a resolution of 3.7 kHz. No self beat signals are observed, establishing that the laser is single mode. By measuring the noise limit of the setup we estimate the mode suppression ratio as greater than 47 dB. A Lorentzian best fit curve of the performed measurement is giving linewidth of 6 kHz.

CONCLUSION

High performance of the fiber ring laser with slope efficiency of 48%, output power of 14.4 mW, threshold of 13.4 mW and tuning range within 3 dB decline of 42 nm have been observed, all in very good agreement with prediction of our model. Single-mode operation with

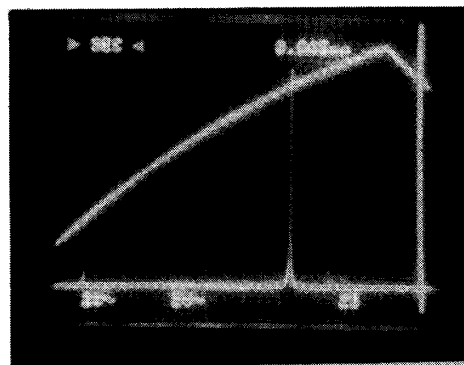


Fig. 5. Spectrum of the fiber laser output measured using a SCFP interferometer (peak). Driving voltage represents one whole FSR of SCFP interferometer.

linewidth of 6 kHz and a mode suppression more than 47 dB have been measured.

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