C-Band Swept Wavelength Erbium-Doped Fiber Laser With a High-Q Tunable Interior-Ridge Silicon Microring Cavity

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Abstract: We demonstrate an erbium-doped fiber laser with a tunable silicon microring cavity. We measured a narrow laser linewidth (16 kHz) and single-mode continuous-wave emission over the C-band (1530nm-to-1560nm) at a swept-wavelength rate of 22,600nm/s or 3106THz/s.
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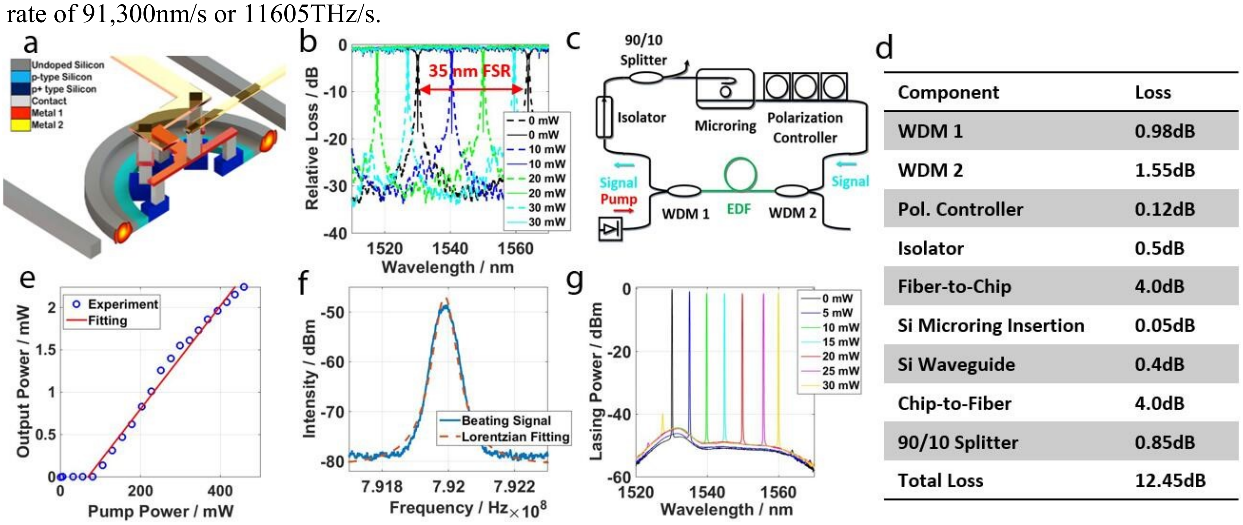
1. Introduction

Compared to lasers using a semiconductor gain medium, lasers based on erbium-doped gain medium have a wide bandwidth across the S, C and L bands. Erbium-doped lasers can achieve a narrow linewidth with deep side mode suppression ratios (SMSR) due to homogeneously-broadened gain. Since erbium can be co-sputtered with its hosts (e.g. silica, alumina or phosphate glass), integration into a CMOS compatible platform is straightforward and the low thermo-optic coefficient of the host media enables operation over a wide temperature range. Erbium-doped waveguide lasers with on-chip SiN cavities have been demonstrated with continuous-wave lasing in the C and L bands without active tunability [1]. Erbium-doped fiber lasers with Si microdisk cavities have also been demonstrated with passive [2] and active [3] wavelength tunability with relatively low efficiency due to losses inside the cavity. More importantly, the frequency modulated and/or swept-wavelength operation of these lasers using on-chip cavities has not been investigated which can lead to integrated sources for frequency-modulated continuous-wave laser imaging, light detection and ranging (FMCW-LIDAR) [4] and optical coherence tomography (OCT) at telecom wavelengths [5-6]. Therefore, a low-loss, high-Q tunable cavity is desired. Recently, we demonstrated a tunable interior-ridge silicon microring cavity filter with an insertion loss as low as 0.05dB and a roughness limited internal Q of 1.5×10^5 [7]. The silicon microring filter had a 3-µm radius and a 35nm free-spectral-range that can be continuously and efficiently tuned (5.5µW power for 1GHz frequency tuning) at high speed (t_f=2.6µs, t_r=1.6µs), shown in Figure 1a-b.

Here, we combine the low-loss tunable interior-ridge silicon microring cavity with an erbium-doped fiber to form a swept-wavelength laser. Laser output power up to 2.2mW with a linewidth of 16±1kHz is measured and the laser is operated with relatively uniform output power over the C-band from 1530nm to 1560nm. When the cavity is rapidly tuned, the swept-wavelength laser response is observed at a mean sweep rate of 22,600nm/s or 3106THz/s and a peak rate of 91,300nm/s or 11605THz/s.



Component	Loss
WDM 1	0.98dB
WDM 2	1.55dB
Pol. Controller	0.12dB
Isolator	0.5dB
Fiber-to-Chip	4.0dB
Si Microring Insertion	0.05dB
Si Waveguide	0.4dB
Chip-to-Fiber	4.0dB
90/10 Splitter	0.85dB
Total Loss	12.45dB

Figure 1 (a) 3D-sketch of the interior-ridge silicon microring cavity. **(b)** The spectral response of the cavity as a function of heater power. **(c)** The erbium-doped fiber laser with the on-chip cavity setup. **(d)**- The loss budget for the laser cavity. (**e**) The laser output power as a function of pump power. **(f)** Linewidth measurement of the laser, showing a narrow linewidth of 16±1kHz. **(g)** Laser output wavelengths at different microring heater levels showing operation across C band.

2. Cavity and Tunable Laser Characterization

The cavity has an embedded Si resistor formed by a low and high dose p-type implants, where the high dose implant is used to thermally isolate contacts from the heater. The resistor acts as a joule heater and it is formed inside the ridge waveguide and attached to the core waveguide. However, doped regions are positioned away from the optical mode, confined into the Si core, and contribute negligible loss to the cavity. The details of the fabrication as well as the design of the cavity are described in [7].

When a 45cm long erbium-doped fiber is pumped and attached to the input and output of the cavity, shown in Figure 1c, the laser output is observed up to 2.2mW via an external power splitter, shown in Figure 1e. Inverted Si tapers are used to couple to the chip, losses within the laser cavity are summarized in Figure 1d. To measure the laser linewidth, the output is passed through a delayed self-heterodyne detection setup, similar to [8]. The laser output is split into two arms and one arm is delayed beyond the coherence length using a 35km fiber placed in a loop with an erbium amplifier and an acousto-optic-modulator at f=44MHz. When the two arms beat at a detector, beat notes ranging from the 1st to 20th harmonics of f are recorded with an electrical spectrum analyzer. A stable and narrow linewidth of 16±1kHz is observed with no coherence artifacts after a delay length of 350km (>10th harmonic) and 18th harmonic (f=18x44MHz=792MHz) electrical response and the Lorentzian fitting is shown in Figure 1f.

3. Swept-Wavelength or Frequency Modulated Operation

When the heater inside the cavity is activated using a DC signal, the laser operates with relatively uniform output power over the C-band from 1530nm-to-1560nm, shown in Figure 1g. When an AC signal ($|2V\bullet\sin(2\pi f_{sweep}t)|$) is placed on top of a DC bias (2.7V), a swept-wavelength laser response covering 1532nm-to-1542nm is measured using an optical spectrum analyzer. This is shown in Figure 2a. This wavelength range is selected to maintain linearity of the wavelength tuning with a sinusoidal heater voltage. For a wider wavelength range, the drive signal needs to be engineered to maintain linearity. A reference SiN cavity with 2.1nm free-spectral-range (Figure 2b) is calibrated with an external highly-stable tunable continuous-wave laser to measure linearity of the wavelength sweep including peak and mean swept rates. The on-chip tunable laser output is passed through the reference SiN cavity and the output is measured with a photodetector and high-speed oscilloscope. When the on-chip tunable laser wavelength coincides with any of the reference resonances during the sweep, the scope records a dip (Figure 2c at f_{sweep}=100Hz). Resonance dips in time are then converted to wavelengths in time using the calibration for excitations at f_{sweep}=100Hz and f_{sweep}=800Hz (Figure 2d and 2e), resulting in mean sweep rates of 2,900nm/s and 22,600nm/s (362THz/s and 3061THz/s) as well as a peak sweep rates of 4,300nm/s and 91,300nm/s (545THz/s and 11605THz/s), respectively. Sweep rates are mainly limited by the relaxation oscillation within the erbium-doped fiber [9].

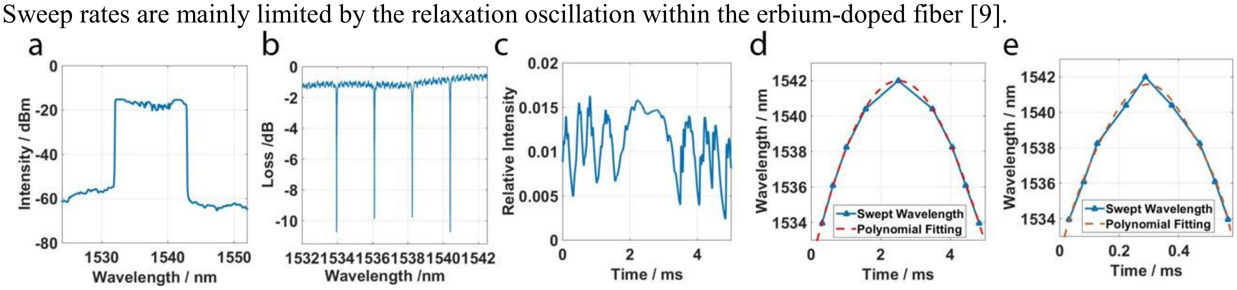


Figure 2 (a) The measured swept-wavelength response with an optical spectrum analyzer using maximum hold setting to show wavelength tuning range. **(b)** The passive spectrum of the reference SiN resonator with 2.1nm free-spectral-range. **(c)** The photodetector output after passing swept-wavelength laser from the reference resonator, dips are corresponding to reference resonances. **(d)** and **(e)** The measured wavelength of the erbium doped fiber laser as a function of time using the reference resonator at sweep frequencies of 100Hz and 800Hz.

4. Conclusions

We successfully demonstrated an erbium-doped fiber laser with a tunable interior-ridge Si microring cavity. Continuous wavelength tuning is achieved over a wide wavelength range (C-band) with output powers up to 2.2mW. The laser with narrow linewidth (16kHz) and high speed swept-wavelength operation (22,600nm/s) is a promising uncooled on-chip FMCW-LIDAR or OCT source.

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