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Slab-Coupled Optical Waveguide Devices for Low-Noise Signal Generation

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Abstract – We review the use of slab-coupled optical waveguide amplifiers (SCOWAs) in low-noise mode-locked and single-frequency lasers. We also report a new single-frequency laser cavity incorporating an Er/Yb-codoped waveguide distributed-Bragg-reflector that produces 330-mW power with 75-kHz linewidth.

Introduction

Over the past decade, dramatic improvements in precision metrology and low-noise signal generation have been realized through the development of mode-locked-laser-based optical frequency combs and single-frequency CW lasers. Ultimately, the noise characteristics of both mode-locked and CW lasers are limited by the quality factor (Q) of the laser cavity and the amount of intracavity optical power. However, this quantum-limited performance is often not obtained due to the presence of other noise sources (*e.g.*, cavity length fluctuations, power-supply noise, 1/f noise).

To date, fiber and solid-state lasers have exhibited superior noise performance relative to semiconductor lasers due to their larger intracavity powers, smaller intracavity losses, and negligible gain/index coupling. The main limitation of fiber and solid-state lasers is that their power conversion efficiency is low (typically < 10%) due to optical pumping inefficiencies. Directly-pumped semiconductor lasers offer the potential of higher power efficiency provided that they can be designed to have sufficient noise performance.

We have recently developed a new class of high-power semiconductor optical gain media referred to as the slab-coupled optical waveguide amplifier (SCOWA) [1]. The SCOWA has several attributes that are beneficial for realizing low-noise optical sources: (i) large (5 x 7 µm) fundamental optical mode due to low index-contrast and mode filtering, (ii) large saturation output power (~ 1 W) due to low optical confinement factor (Γ), and (iii) small excess optical loss due to low overlap between the mode and the high-loss p-doped cladding layers. SCOWA applications that have been demonstrated at 1.5-µm include Watt-class power amplifiers, actively mode-locked external-cavity lasers (ECLs) with record-low timing jitter, monolithic passively mode-locked lasers with > 200-mW power, and single-frequency fiber Bragg-grating (FBG) SCOWA-based ECLs (SCOWECLs) producing 90-mW power with ~150-kHz linewidth [2].

In this talk we will review the operating principles of the SCOWA technology and its use in low-noise mode-locked and single-frequency lasers. We report improved FBG SCOWECL performance. We also demonstrate a novel ECL having an external cavity comprising an Er/Yb codoped waveguide distributed Bragg-reflector (DBR).

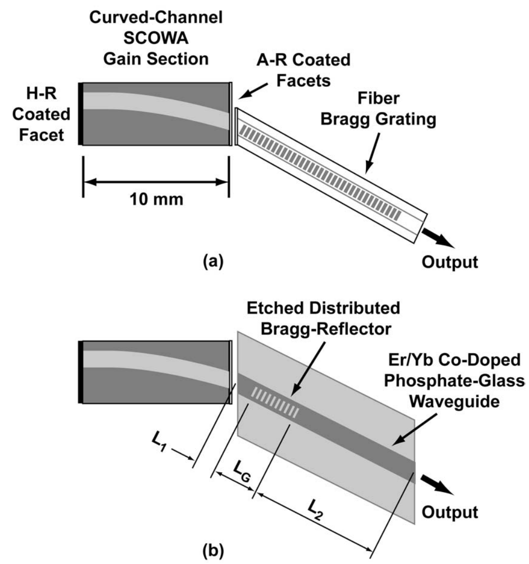

Fig. 1. SCOWA-based 1.5-µm single-frequency lasers having different external cavities: (a) narrow-bandwidth (6.2 GHz) fiber Bragg grating, (b) Er/Yb co-doped phosphate-glass waveguide with distributed Bragg reflector (DBR). Er-DBR waveguide dimensions: L_1 = 1 mm, L_G = 6 mm, L_2 = 9 mm.

Single-Frequency External-Cavity Lasers

A primary issue in realizing single-frequency semiconductor ECLs is designing the cavity to maintain stable, single-longitudinal-mode operation with high side-mode suppression. To achieve single-frequency operation, a frequency-selective element must be included in the cavity to reduce the optical bandwidth, thereby allowing only a single mode to oscillate. The narrow bandwidth required becomes increasingly difficult to attain as the length of the active gain medium increases. We examine two external cavities that enable stable single-mode operation with a long (10 mm) SCOWA gain section. First, we use a long FBG that contains only a few longitudinal modes within its bandwidth. And second, we use a Er/Yb-codoped waveguide containing a relatively short DBR. This doped-cavity approach has previously been used to stabilize semiconductor ECLs comprising meter-length doped-fiber external cavites [3]-[4].

Figure 1 depicts the two SCOWECL cavities that were investigated. Both cavities utilize the same curved-channel InGaAsP quantum-well SCOWA (10-mm length, 100-mm radius) having a high-reflectivity (R > 95%) rear facet and a 5°-angled, anti-reflection (AR) coated front facet [5]. The AR-coated SCOWA facet is directly butt coupled to either an angle-cleaved FBG (Fig. 1(a)) or an angle-polished Er-DBR

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waveguide (Fig. 1(b)).

FBG SCOWECLs were evaluated at three different wavelengths spanning the SCOWA gain bandwidth using FBGs fabricated in HI1060 Flex fiber and having center wavelengths of 1480, 1520, and 1556 nm. The bandwidth and reflectivity of the FBGs were 50 pm (6.2 GHz) and 50%, respectively. The FBGs were angle cleaved at 11° and AR-coated. The distance between the angled fiber facet and the beginning of the FBG was < 2 mm. The mode-diameter of the HI1060 Flex fiber (6.5 μm) is well matched to the large mode profile of the SCOWA (6 x 7.5 μm), enabling butt-coupling efficiency > 60%.

For the three FBG wavelengths evaluated, the best performance was obtained at 1520 nm, which is on the short-wavelength ("blue") side of the gain spectrum peak at the threshold current of 700 mA. Single-mode operation was verified using a scanning Fabry-Perot interferometer. At I = 2.9 A, the output power was 200 mW and the FWHM linewidth was 40 kHz. Self-heterodyne linewidth measurements (Fig. 2) revealed a Lorentzian lineshape, indicating that white noise was dominant. The threshold currents for both the 1480- and 1556-nm FBGs increased to about 1 A due to the lower gain at these wavelengths. The single-longitudinal-mode stability was notably worse at 1556 nm. We attribute this mode instability to operation on the long-wavelength ("red") side of the gain spectrum where the linewidth enhancement factor (α) is larger.

The Er/Yb-codoped DBR phosphate-glass waveguide used here was previously used to realize optically pumped 1.5-μm single-frequency lasers producing 80-mW power and 500-kHz linewidth [6]. In our work, the waveguide facets were polished at a 10° angle to reduce the facet reflectivity and allow efficient butt-coupling. The facets were not AR coated. The dimensions shown in Fig. 1(b) are L_1 = 1 mm, L_G = 6 mm, and L_2 = 10 mm. For this grating length, the DBR bandwidth is approximately 270 pm (33 GHz) and contains many longitudinal modes. The etched DBR center wavelength is 1539 nm and the estimated reflectivity is 65%.

The threshold current for the Er-DBR SCOWECL was 750 mA, which is nearly equal to that of the 1520-nm FBG SCOWECL. Self-heterodyne linewidth measurements (Fig. 3) revealed a Voigt lineshape with Gaussian (Lorentzian) linewidths increasing from 56 to 75 kHz (5.0 to 7.2 kHz) as the current was increased from 1.2 to 3.0 A. The output power at I = 3 A was 330 mW. To our knowledge, this combination of high output power and narrow linewidth is the best that has been achieved for semiconductor ECLs.

Conclusions

We have demonstrated two semiconductor ECL geometries containing a high-power SCOWA gain medium that provide stable single-longitudinal-mode operation. The Er-DBR cavity has higher output power than the FBG cavity (330 vs. 200 mW at ~3 A bias). The lineshapes of the two cavities are considerably different. At I ~ 3A, the total FWHM linewidth of the Er-DBR cavity is almost twice as large as that of the FBG cavity (75 vs. 40 kHz). However, the Er-DBR Voigt lineshape has a 7.2-kHz Lorentzian component so that the phase noise decreases much faster than that of the FBG ECL.

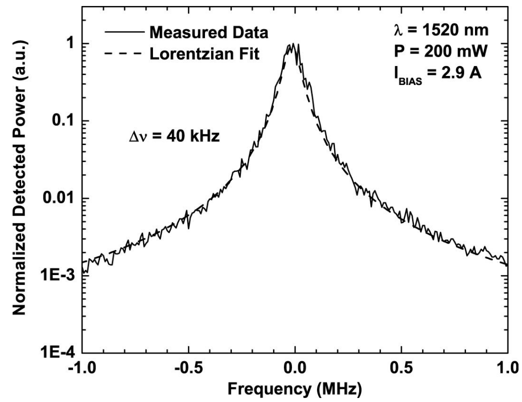

Fig. 2. Self-heterodyne linewidth measurement of SCOW external-cavity laser incorporating a 1520-nm HI1060 Flex fiber Bragg grating. Fiber delay = 25 km (125 μs).

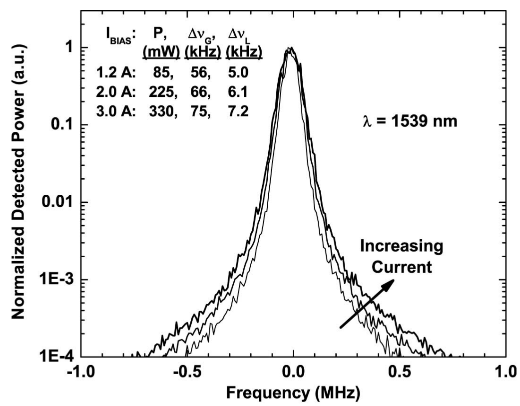

Fig. 3. Self-heterodyne linewidth measurement of SCOW external-cavity laser incorporating a Er/Yb codoped waveguide with DBR. Fiber delay = 25 km (125 μs).

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