637-nm Hybrid-Integrated Diode Laser

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We present the first hybrid integrated extended cavity diode laser (ECDL) tunable around 637 nm. This wavelength range is important for excitation of nitrogen vacancy centers (NV) in diamond, one of the leading platforms for quantum information processing. The laser comprises a custom designed Si_3N_4 circuit using high-confinement, low-loss, double-stripe waveguides to provide frequency selective feedback to a semiconductor optical amplifier (SOA). The SOA, a tilted-waveguide GaAs double-pass amplifier, and the Si_3N_4 feedback circuit are hybrid integrated using tapers for mode matching. Two microring resonators in the feedback circuit serve for single-wavelength operation and wide tuning. The laser shows a threshold pump current of 50 mA with 0.26 mW fiber-coupled output power. The laser can be tuned across the full gain bandwidth of 6 nm, including the NV-center target wavelength.

Introduction

Photonic quantum technologies, including applications such as chip-integrated optical clocks, quantum-key distribution systems and photonic quantum processors are being developed at a rapid speed [1]. Upscaling of such systems calls for chip-integrated lasers to be used as sources. While infrared integrated lasers at telecom wavelengths are already mature, many of the applications require integrated visible lasers that do not yet exist, e.g., for addressing particular atomic and ionic transitions, quantum dots or nitrogen vacancy centers. Chip integration and spectral control of such sources appears feasible by exploiting the wide transparency range and high index contrast of the Si_3N_4 / SiO_2 platform, to provide low-loss waveguide circuits [2] for the visible range [3].

An important step was the first demonstration of a visible hybrid-integrated laser [4] in the silicon nitride platform. The laser operates around a center wavelength of 685 nm, such as to address transitions in strontium. As the basic approach, an extended cavity diode laser design was chosen because this can offer free tunability and wide spectral coverage, single-frequency operation, and ultranarrow linewidth. A subsequent approach for visible output was self-injection locking of Fabry-Perot (FP) diode lasers [5]. There, however, laser emission is bound to predefined FP modes and requires a proper feedback phase for temporally stable operation.

Here, we present the first hybrid integrated extended cavity diode laser (ECDL) operating at wavelengths around 637 nm, which is of interest for targeting nitrogen vacancy centers [6]. The laser is tunable over the entire gain bandwidth, using the Si_3N_4 platform with a custom designed waveguide cross section for low-loss dual-ring Vernier filter feedback.

Waveguide Design and Characterization

To realize a proper feedback circuit for the 637-nm range in the Si_3N_4 waveguide platform, we designed a dedicated waveguide cross section as displayed in Fig. 1(a).

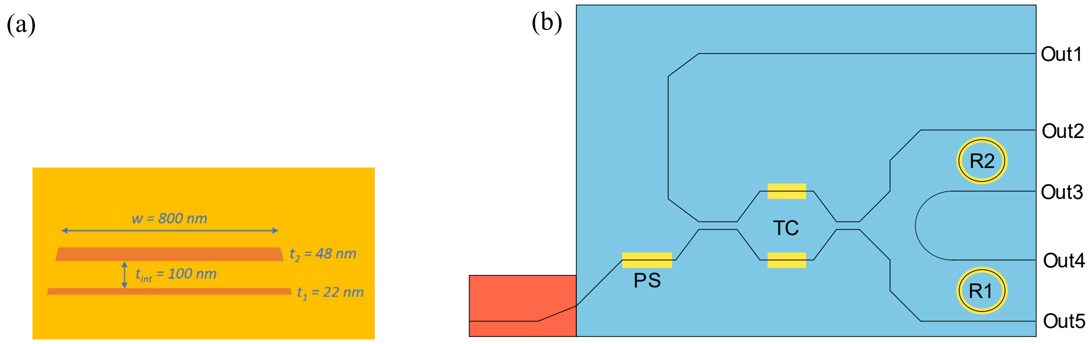

Figure 1. (a) Custom designed double-stripe waveguide cross-section to provide low propagation and bend loss in the visible (red: Si_3N_4 core, yellow: SiO_2 cladding. (b) Schematic drawing of the extended cavity laser with a GaAs semiconductor optical amplifier on the left (in red) coupled to a Si_3N_4 feedback circuit (in blue). Thermo-optic heaters are implemented for tuning of the overall cavity length with a phase section (PS), to tune the output coupling (TC) and to tune the laser wavelength via the optical length of the microring resonators (R1, R2). The first port is the main output port of the laser, while the other ports serve as monitor ports.

The design procedure aimed on enabling low propagation loss and low bend loss, to enable short microring resonators with a large free spectral range and high spectral selectivity. These properties are required for single-frequency oscillation with high side-mode suppression, and for expanding tunability across the full gain bandwidth of the diode amplifier. Losses expected from sidewall scattering were estimated via path integrals of the mode intensity along the waveguide. To avoid scattering into higher-order modes, we restricted the design to cross-sections that guide only a single transverse mode. Mode field distributions were calculated with a 2D finite difference mode solver [7] to optimize the core geometry parameters along the following guidelines: Increasing the aspect ratio of the SiN cores minimizes loss from sidewall scattering. Thicker cores and a double-stripe geometry (compared to a single stripe) provide tighter guiding for minimizing bend loss. During the optimization, we restricted the cross sections to negligible bend loss ($\leq$ 0.01dB/cm) for bend radii down to 100 µm. 2D tapers were designed for mode matching to a semiconductor optical amplifier (SOA) and to output fibers. To provide high fabrication fidelity at small feature size, and to obtain smoother sidewall surfaces than with contact lithography, fabrication was carried out via DUV stepper lithography.

To verify the intended properties of the new cross section and circuit components, an experimental characterization is required before integration with a SOA. Of central interest is quantifying the propagation loss, specifically, in a single pass over longer propagation length. Directional couplers were characterized as well, as these determine, together with waveguide losses, the frequency selectivity of the laser feedback from the microring resonators. Fig. 2(a) shows the measured propagation loss vs wavelength, as measured using a 47 cm long waveguide spiral. For the target wavelength of 637 nm, the propagation loss is 0.33 dB/cm. Decreasing losses at longer wavelengths can be addressed to reduced scattering, while increasing loss (beyond 720 nm) is due to bend loss. Fig. 2(b) shows the measured wavelength dependent coupling strengths (traces) compared to the target values (horizontal lines). We find satisfying agreement, with a somewhat higher coupling than the nominal target values.

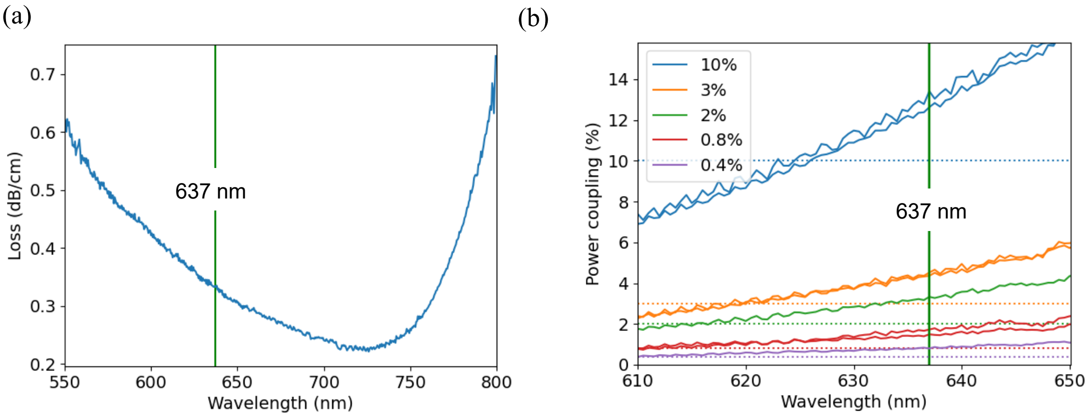

Figure 2: (a) Propagation loss measured in single-pass with a 47-cm long spiral. (b) Measured wavelength dependence of directional couplers (solid traces) compared with target values (horizontal dotted lines).

Hybrid integrated laser design and fabrication

The overall design of the laser is depicted in Fig. 1(b). The waveguide circuit forms an ECDL comprising tunable microring resonators in Vernier configuration [8] and a double-pass GaAs semiconductor optical amplifier (SOA). The reflective back facet of the SOA acts as one mirror of the laser cavity, while the Vernier feedback circuit acts as the other cavity mirror. The SOA is a super-luminescent diode (SLED) with a center wavelength of 638 nm. For double-pass amplification, the back facet has a high-reflectivity coating (>95%). To reduce undesired feedback from the SOA output facet, the ridge waveguide of the SLED is curved to form an angle with the surface normal. Additionally, the output facet is anti-reflection coated (<0.1%).

On the feedback chip, two micro-ring resonators (R1 and R2) with respective radii of 100 and 103 µm and nominal 0.8% couplers form a Vernier filter with high side-mode suppression over a 14 nm wide free spectral range. This aims on enabling single-wavelength operation over the entire gain bandwidth. Thin film electric heaters are implemented to tune the overall cavity length with a phase section (PS), tune the Vernier filter, and to provide tunable output coupling (TC) via the first port (Out1). The other ports can deliver additional output or serve as monitor ports. The SOA and feedback chips are hybrid-integrated on a thermo-electric cooler. The laser is packaged in a butterfly housing with electric wire bonding and a fiber array at the laser output ports.

Laser operation and wavelength tuning

The laser is operated using a laser driver (Chilas TLC), a temperature controller (Thorlabs TED200) and a diode laser current source (ILX Lightwave LDX-3620). For simultaneous recording of the laser output power and spectra, the fiber-coupled laser output is sent via a calibrated fiber splitter to a power meter (Thorlabs PM100D) and an optical spectrum analyzer (OSA, ANDO AQ6317).

Figure 3(a) shows the laser output power vs. diode laser drive current, as recorded from the first port (Out1). In this recording, the laser wavelength is set to 638.6 nm. Upon increasing the pump current, with fixed heater powers at R1, R2, and the phase section, we find a laser threshold current of around 50 mA. At 72 mA pump current, the laser output power is 0.26 mW. The variations of output power vs pump current can be addressed to longitudinal mode-hops caused by index changes in the diode amplifier.

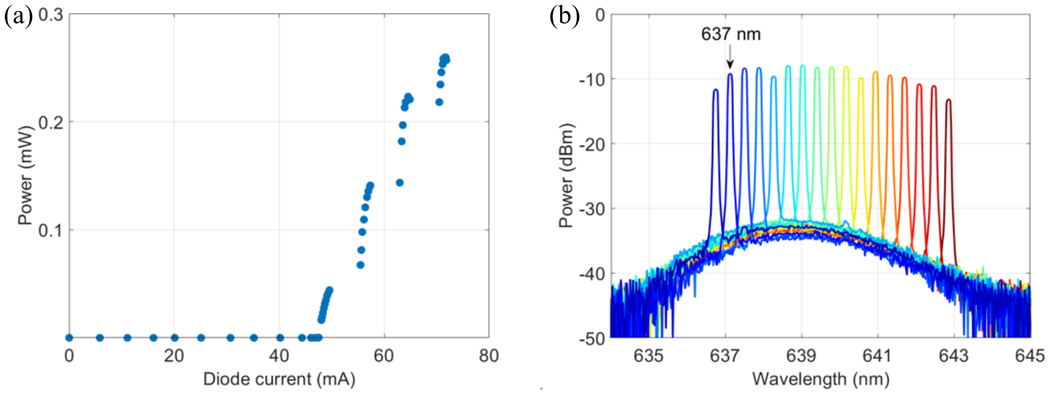

Figure 3: (a) Measured fiber-coupled output power at a laser wavelength of 638.6 nm. The output power is 0.26 mW at 72 mA pump current. (b) Laser output spectra measured with a constant pump current of 66.87 mA and the spectral resolution set to 0.1 nm. 17 traces, each showing single-wavelength emission, are recorded with stepwise tuning the heater power of microring R1 in the range between 58 and 231 mW (lower wavelengths correspond to higher power). The approximate wavelength of diamond NV centers is indicated with an arrow.

Figure 3(b) shows a superimposed series of output spectra from port Out2, recorded using the OSA with the resolution set to 0.1 nm. The experiment was carried out with a fixed pump current of 66.87 mA and stepwise varying the heater power at R1 in the range between 58 and 231 mW. Analogous tuning is expected when acting on the R2 heater. The recordings show a wavelength tuning range of more than 6 nm.

The hybrid laser demonstrated here can be tuned across the wavelength range of NV color centers in diamond [6], which complements integration and upscaling for circuits with embedded NV single photon emitters [9].

Acknowledgments

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