Realization of a Hybrid Integrated Diode laser for Visible Light

Student Paper

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ABSTRACT

Hybrid integration of a semiconductor amplifier with a feedback circuit containing ring resonators has been widely demonstrated in the infrared. Such lasers provide ultra-narrowband and single-mode oscillation, which can be tuned over a large spectral range, and easily integrated in a photonic circuit. Contrary to this, applications in the visible spectral range, such as precision metrology with optical clocks, rely on bulk optics lasers, which are susceptible to acoustic noise as they cannot be integrated on a chip. To realize hybrid integrated lasers in the visible range, where scattering losses are typically higher than in the infrared, it is required to design a feedback circuit based on low-loss waveguides. Here, we present the first design and realization of a hybrid integrated diode laser in the visible, by integrating an AlGaInP based amplifier with a Si_3N_4 based feedback circuit. Our experimental results show that the laser can be tuned over a 11 nm wide interval around the central wavelength of 685 nm and that it delivers a single wavelength output power of up to 4.8 mW. This result is of great importance for the development of on-chip narrowband and tuneable light sources in the visible range.

Keywords: semiconductor laser, hybrid integration, visible light, silicon nitride, low-loss waveguides

1. INTRODUCTION

Over the last years, several photonic platforms have emerged for the visible range [1]. These platforms allow integration of bulk optical components in a small form factor, which provides stability and a reduction in size, weight and costs. Photonic integration in the visible range is of high interest for applications in bio-photonics [2] and metrology, but also for portable atomic clocks [3] or quantum computing with trapped ions [4]. Even though photonic integration platforms are well-developed, they still require the use of external lasers.

In the infrared, hybrid integrated lasers, by integration of a semiconductor amplifier with a low-loss feedback circuit have been demonstrated. These lasers provide single wavelength operation with sub-100-Hz intrinsic linewidths, and can be tuned over a large wavelength range [5]. This concept has been demonstrated for telecom application around 1550 nm and, with a few exceptions, at other infrared wavelengths, for example at 850 nm [6] and 1 µm [7]. Further extension towards the visible range is difficult, because absorption and scattering hinder low-loss feedback from a dielectric circuit, which is essential in constructing a hybrid laser.

Here, we design a hybrid laser for wavelengths around 685 nm, based on weakly guiding and low-loss Si_3N_4 waveguides and show, for the first time, operation in the visible range.

2. HYBRID LASER DESIGN

A schematic of the chip design is shown in Fig. 1 (a). The laser comprises an AlGaInP based amplifier, which is hybrid integrated with a Si_3N_4 based feedback circuit. One mirror of the laser cavity is formed by a high-reflective (HR) coating on the amplifier chip, while the other mirror is formed by the feedback circuit. The function of the feedback circuit is i) to provide frequency selective feedback to restrict oscillation to a single cavity mode, and ii) to extend the cavity length with low losses to extend the photon lifetime, which reduces the laser's intrinsic linewidth.

Key in this design for the visible range is a proper waveguide cross section, which provides low propagation losses. For this feedback circuit we use the TriPleX^{TM} platform due to its wide transparency range, which extends down to 400 nm wavelength [8]. The platform also enables lateral tapering of the waveguides at the facet, which we used to minimize coupling losses with the gain chip and for efficient single-mode fibre output coupling. To reduce scattering losses, we exploit the weak mode confinement of a 2 µm wide and 25 nm thick single stripe Si_3N_4 buried in a SiO_2 cladding. As a consequence of the weak mode confinement, the minimum bend radius is 1200 µm for negligible bend losses. Therefore, microring resonator (MRR) radii are chosen as 1200 and 1205 µm, for MRR1 and MRR2, respectively. The slight difference in radii allows the sequential ring resonators to function as a Vernier filter to select a single cavity mode within the gain bandwidth of the amplifier. To tune the microring resonances, heaters are placed on top of the microring resonators to work as thermoelectric phase shifters. Similarly, a so-called phase section is present to tune the optical length of the laser cavity.

To enable stable operation of the laser, the amplifier chip, feedback chip and output fibre are hybrid integrated. All tuneable elements are wire bonded to electrical contacts, which allows control by external current sources and power supplies.

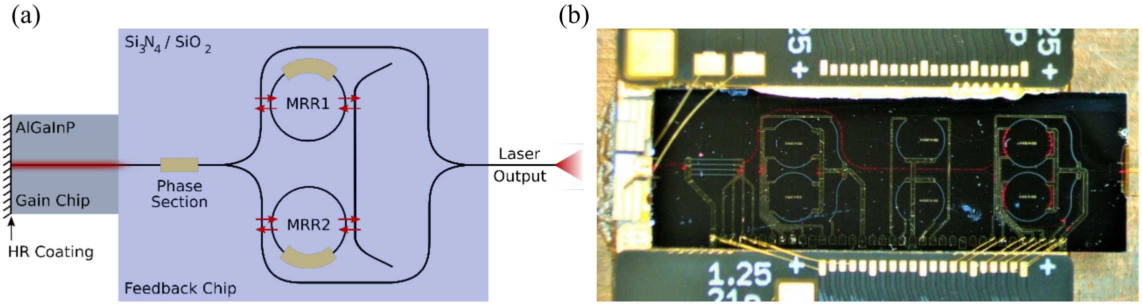

Figure 1. a) Schematic overview of the hybrid laser comprising a gain chip and a feedback circuit based on two high-Q microring resonators (MRR1 and MRR2). Thermoelectric phase shifters are indicated in yellow. b) Photo of the laser during operation. A pair of microring resonators (on the right hand side of the feedback chip) provides frequency selective feedback. Due to the resonant build-up of light in the resonators and weak scattering of light in the waveguides, the red colour of the light is clearly visible.

Figure 1 (b) shows a photo of the final assembly of the hybrid laser, where the laser is turned on by supplying current to the amplifier. In the shown case, the pair of ring resonators located on the right hand side of the feedback chip provides the frequency selective feedback to the amplifier. Due to the resonant build-up of light in these resonators and due to weak scattering of the light in the waveguides, these rings are brightly lit with the red colour of the laser light. Fig. 1 (b) confirms, for the first time, the operation of a hybrid diode laser in the visible spectral range.

3. EXPERIMENTAL RESULTS

Figure 2 gives an overview of the laser's output power and tuning characteristics. The fibre-coupled output power as measured vs. the pump current of the amplifier is shown Fig. 2 (a), and Fig. 2(b) shows the overall spectral coverage. The power was measured by connecting the output fibre of the laser with a 50/50 coupler and a photodiode power sensor and by correcting the output power with the losses through the coupler. During such measurement, while increasing the pump current, the laser's carrier was kept at a temperature of 20° C. Only the heater on the phase section was optimized for maximum output power (MRR heaters not actuated). We determined the threshold current at 46 mA. Above this value, the output power increases approximately linearly. Deviations from the linear trend can be attributed to mode hops, due to the index changes in the semiconductor material when the current and, consequently, the internal diode temperature would increase. For the maximum specified pump current of 90 mA, the output power is found to be 4.80 mW. Estimating the chip-to-fibre coupling losses as approximately -1 dB, an on-chip optical power of about 6 mW is available for further on-chip processing in fully integrated applications. For this setting, we also measured the spectral characteristics of the light output with an optical spectrum analyser (OSA, ANDO AQ6317, resolution bandwidth of 0.01 nm) and found single-mode oscillation within the resolution limit.

Figure 2 (b) shows several superimposed laser spectra, as measured with the OSA, while the electrical power supplied to the heater of MRR1 was varied in steps of 25 mW. For each measurement, the phase section was optimized under inspection with the OSA in order to obtain a single-mode operation. From these spectra, we observe that the laser wavelength can be tuned over 11 nm around 685 nm, which corresponds to the gain bandwidth of the amplifier as indicated by the black dotted lines in Fig. 2 (b). The gain bandwidth was measured before hybrid integration via recording the spectrum of amplified spontaneous emission of the solitary amplifier chip. As expected, the highest output power was measured near then peak of the gain spectrum. These measurements also show that the laser wavelength can be controlled by setting the ring resonators, which confirms that the laser indeed operates based on feedback from the Si_3N_4 circuit.

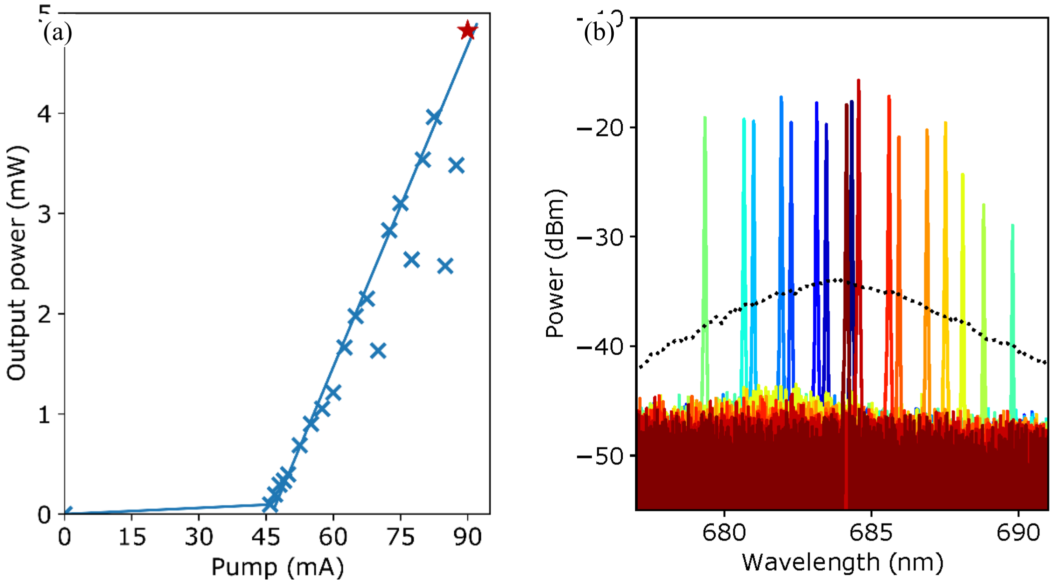

Figure 2. a) Measured fibre-coupled output power of the laser as function of the pump current to the amplifier. The maximum measured power of 4.80 mW (6 mW on chip) is indicated with a star. Comparison with a straight line drawn through the data points of maximum power indicates an approximately linear increase of the output with pump current. b) Superimposed laser spectra as measured with an OSA (resolution bandwidth 0.01 nm), showing an 11 nm wide tuning range of the hybrid laser around 685 nm. In order to obtain these spectra, MRR1 was heated between 0 and 400 mW in steps op 25 mW, while the pump current was set to 75 mA. The dotted black line shows the amplified spontaneous emission (ASE) of the solitary amplifier chip recorded before hybrid integration .

4. CONCLUSIONS

We realized, for the first time, a hybrid integrated diode laser for the visible range. To provide frequency selective feedback with very low losses, a Si_3N_4 based feedback circuit has been designed. Si_3N_4 based waveguides provide negligible absorption losses in the visible range, while the weak mode confinement of the optimized waveguide cross section reduces sidewall scattering losses. The demonstrated tuning range of the hybrid laser spans an 11 nm wide interval around 685 nm. A maximum output power of 4.8 mW has been measured at the maximum gain current of 90 mA. This demonstration in the visible range can form a breakthrough for applications which require tuneable and narrowband light sources on a chip. Further extension of this concept towards lower wavelength appears feasible, given the excellent transparency of the Si_3N_4 platform down to 400 nm.

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