Best Student Paper Award

A hybrid semiconductor-glass waveguide laser

Youwen Fan[1*], Ruud M. Oldenbeuving[1,2], Edwin J. Klein[3], Chris J. Lee[1,4,5], Hong Song[6,7], Muhammed R. H. Khan[8], Herman L. Offerhaus[9], Peter J. M. van der Slot[1] and Klaus-J. Boller[1]

[1] Laser Physics and Nonlinear Optics group, MESA+ Institute for Nanotechnology,
University of Twente, Enschede, The Netherlands
[2]SATRAX B.V., Enschede, The Netherlands
[3]XiO Photonics B.V., Enschede, The Netherlands
[4]XUV Optics group, MESA+ Institute for Nanotechnology,
University of Twente, Enschede, The Netherlands
[5]FOM Institute DIFFER, Nieuwegein, The Netherlands
[6]Delft Center for Systems and Control, Delft University of Technology,
Delft, The Netherlands
[7]Institute of Underwater Technology and Ship Engineering,
Zhejiang University, Hangzhou, China
[8]Telecommunication Engineering Group, Centre for Telematics and Information Technology,
University of Twente, Enschede, The Netherlands
[9]Optical Sciences group, MESA+ Institute for Nanotechnology,
University of Twente, Enschede, The Netherlands
[*]E-mail:y.fan@utwente.nl

ABSTRACT

We report on a novel type of laser in which a semiconductor optical amplifier (SOA) receives frequency-selective feedback from a glass-waveguide circuit. The laser we present here is based on InP for operation in the 1.55 μm wavelength range. The Si_3N_4/SiO_2 glass waveguide circuit comprises two sequential high-Q ring resonators. Adiabatic tapering is used for maximizing the feedback. The laser shows single-frequency oscillation with a record-narrow spectral linewidth of 24 kHz at an output power of 5.7 mW. The hybrid laser can be tuned over a broad range of 46.8 nm (1531 nm to 1577.8 nm). Such InP-glass hybrid lasers can be of great interest in dense wavelength division multiplexing (DWDM) and as phase reference in optical beam-forming networks (OBFN). The type of laser demonstrated here is also of general importance because it may be applied over a huge wavelength range including the visible, limited only by the transparency of glass (400 nm to 2.35 μm).

Keywords: external feedback, microring resonator,semiconductor, glass waveguide, narrow linewidth, tunable laser

1. INTRODUCTION

New developments in laser technology are of both fundamental and technological interest and enable numerous applications. Of special interest are tunable lasers with narrow spectral linewidth, for which external cavity diode lasers (ECDLs) are important candidates. However, in such lasers the external frequency-selective feedback is usually achieved with bulk optical components, which renders such lasers unsuitable for many applications where small size is required. Furthermore, the mechanical tuning scheme limits the switching time between different wavelengths to tens of ms,[1,2] while a design with bulk components is prone to acoustic perturbations. These issues can be addressed with monolithic integration such as found in distributed Bragg reflector (DBR) lasers and distributed feedback (DFB) lasers. But the spectral linewidth so far achieved with DFB and DBR lasers is typically in the order of MHz, along with a small tuning range around a few nm.[3,4]

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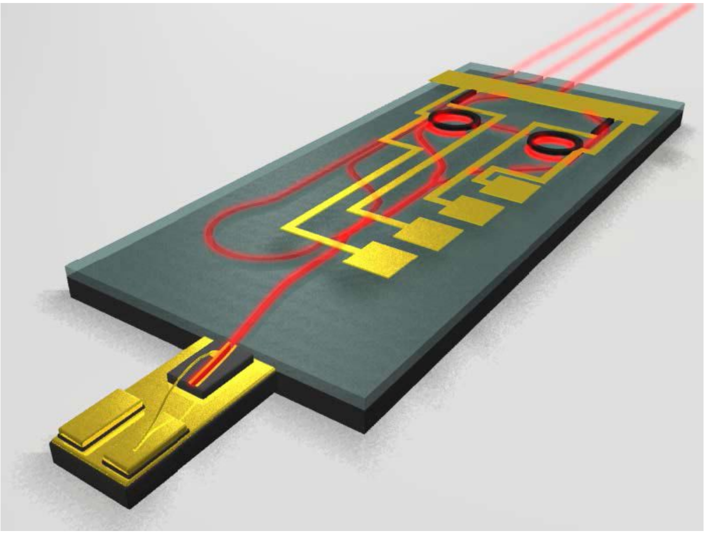

Figure 1. Schematic illustration of the hybrid semiconductor-glass waveguide laser

In this work we report on a novel type of laser in which components with complementary (active versus passive) properties are combined. Wide tunability and a record narrow linewidth are demonstrated with this type of laser while the footprint is kept small (a few mm). The construction of the laser is depicted in Fig. 1. The light generated by a solitary semiconductor optical amplifier (SOA) is controlled by frequency selective feedback from a glass-waveguide circuit which incorporates two microring resonators (MRRs). The control yields single-frequency oscillation and a wide wavelength tunability. Choosing MRRs with high quality factors enhances the frequency selectivity. Choosing glass waveguides with low loss enables an increasing of the feedback path lengths for narrowing the spectral laser linewidth. The shown type of laser may be straightforwardly extended to operate over a wide spectral region including the entire visible range, due to the wide transparency range of glass waveguides (400 nm to 2.35 μm),[5] when making use of amplifiers from different semiconductor materials, such as GaN, GaAs or InGaAsSb/AlGaAsSb. Compared to initial our results,[6] using an improved design with tapered glass waveguides, we demonstrate here a factor of ten increase in output power and an enlarged spectral coverage.

2. STRUCTURE AND OPERATION PRINCIPLE

As is shown in Fig. 1, the hybrid laser features an active-passive structure, comprising a solitary InP SOA chip and a dedicate glass waveguide circuit. To more detail, one of the facets of the amplifier chip is equipped with a high reflection (HR) coating, while the other facet (facing the glass chip) is anti-reflection (AR) coated, to suppress lasing within the gain chip. To further decrease residual feedback from the AR facet, the waveguide of the gain chip is tilted at 5 degrees with respect to the facet normal. Wire-bonding is used for current injection while the gain chip is mounted on a Si heatsink for the purpose of temperature stabilization. The chip is butt-coupled to the external glass waveguide circuit, the key component of which is a mirror-like circuitry (MRR mirror) composed of two sequential MRRs with slightly different radii. Due to the Vernier effect, a much larger free spectral range (FSR) can be achieved than with a single MRR .[7,8] A large FSR is preferable for wide range tuning while maintaining single-mode operation. Lasing wavelength selection can be accomplished through thermally tuning the optical length of the MRRs via chromium heaters deposited on top of the resonators. The large index contrast ($\Delta n = 0.5$) of Si_3N_4/SiO_2 waveguides brings a considerable decrease in size compared to that, e.g., achieved with silica on silicon.[5] Additionally, propagation losses are low due to the smooth Si_3N_4/SiO_2 interfaces that can be provided with these amorphous materials. For example, propagation losses of typically 0.06-0.08 dB/cm can be achieved across the entire telecommunication C-band ,[9] which are nearly two orders of magnitude lower than the commonly obtained 3 dB/cm with Si/SiO_2 waveguides .[10–13] Also Si_3N_4/SiO_2 waveguides with a record low

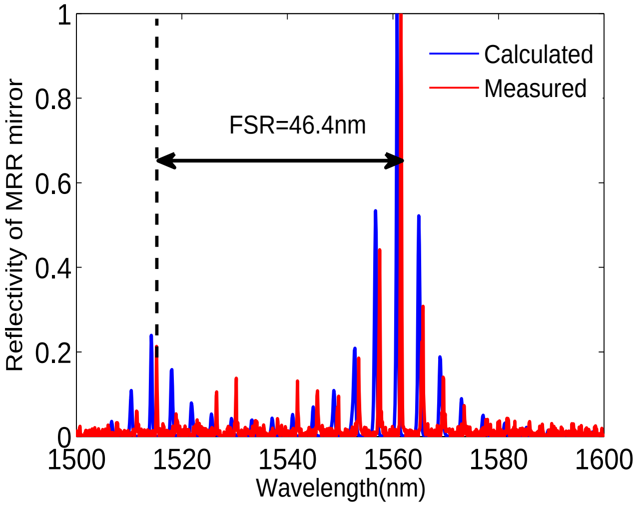

Figure 2. Calculated (blue) and measured (red) reflectivity as a function of wavelength of the double microring resonator mirror

loss of 0.007 dB/cm has been reported recently.[14] It can be clearly seen that advantages associated with the utilization of Si_3N_4/SiO_2 waveguides over other types of waveguides are prominent.

Another key issue of combining a solitary laser with an external waveguide is mode matching between the two. Undesired loss occurs when the mode profile in the gain waveguide differs from that in the passive waveguide. This is detrimental because it lowers the output power and increases the laser linewidth as well .[6] To address this, we have implemented an adiabatic taper section in the external waveguide circuit. Based on the design parameters chosen for reliable fabrication we determine a high coupling efficiency of 80%, which decreases undesired losses to about 20%.

3. EXPERIMENTAL RESULTS

In this section the properties of the hybrid laser are discussed in detail. The radii of the two MRRs are 49.5 μm and 54 μm respectively and via the waveguide cross section the group refractive index of the waveguide is designed as 1.78, resulting in a calculated total FSR of 47.7 nm. The output of the hybrid laser is collected using a polarization maintaining (PM) fiber and then fed into a high resolution (0.01 nm) optical spectrum analyzer (OSA).

3.1 MRR mirror properties

A broadband optical source (superluminescent diode) emitting light from 1500 nm to 1600 nm is used to measure the reflectivity of the MRR mirror as a function of wavelength. These measurements are done to confirm the successful fabrication of the design. In Fig. 2 we present a typical example of both a calculated and a measured reflectivity spectrum. The measured spectrum is normalized to its peak reflectivity which is 48%. It can be seen that the spectra, after normalization, are in excellent agreement with each other. The double-ring arrangement provides a relatively large free spectral range (FSR) of 46.4nm. This is promising in terms of wide tunability across the entire bandwidth of the gain chip while maintaining a single-wavelength output. The relatively small spectral width of the central maximum (0.19 nm) and the low reflectivity of the first side peak (22%) are desirable for single-mode operation.

3.2 Emission spectrum

Figure 3 shows the output spectrum of the hybrid laser when operating at a driving current of 90 mA which is far above the threshold (5 mA). The output power is 5.7 mW of which 2 mW is coupled into the fiber for spectral

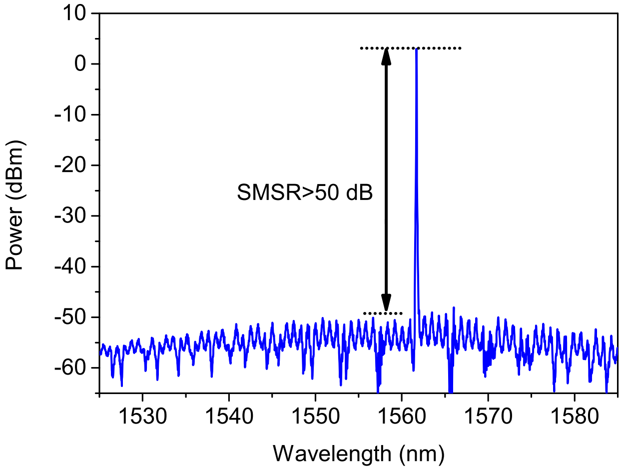

Figure 3. Single-wavelength laser spectrum obtained at a driving current of 90 mA, the measured side mode suppression ratio (SMSR) is larger than 50 dB.

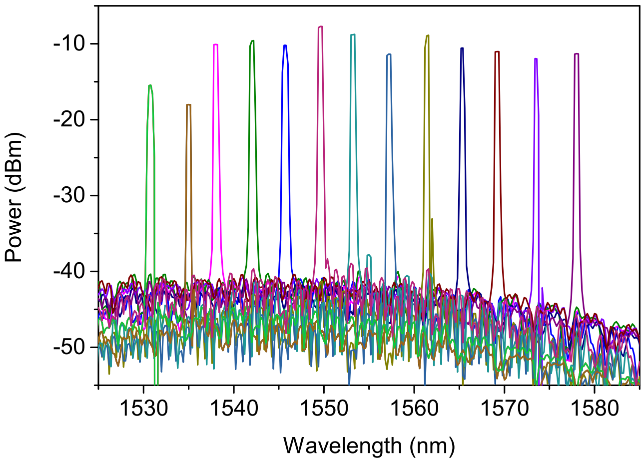

Figure 4. Superimposed output spectra of the hybrid laser obtained at driving current of 70 mA

analysis. It can be seen that the side mode suppression ratio (SMSR) is higher than 50 dB which suffices in almost all of the applications where there is a high demand for spectral purity.[15, 16]

In order to measure the tuning range of the hybrid laser, a continuously increasing voltage is applied to the heater of one of the MRRs. This resulted in stepwise tuning of the the wavelength with the FSR of the other MRR. Wavelengths larger than 1561.7 nm are obtained by heating the MRR with the larger radius (54 μm) while shorter wavelengths are achieved by tuning the smaller MRR (49.4 μm) at a driving current of 70 mA. Figure 4 shows that the hybrid laser can be tuned over a broad range starting from 1531 nm, towards 1577.8 nm, amounting to 46.8 nm, which is approximately 1.5-times larger than the telecommunication C-band (35 nm). We note that the measured tuning range matches well with the FSR found in Fig. 2 as expected.

3.3 Linewidth measurement

To resolve the linewidth of the hybrid laser beyond the resolution of the OSA we employ delayed self-heterodyne detection. A 30 km long fiber is used to provide a delay longer than the coherence time of the laser. Considering

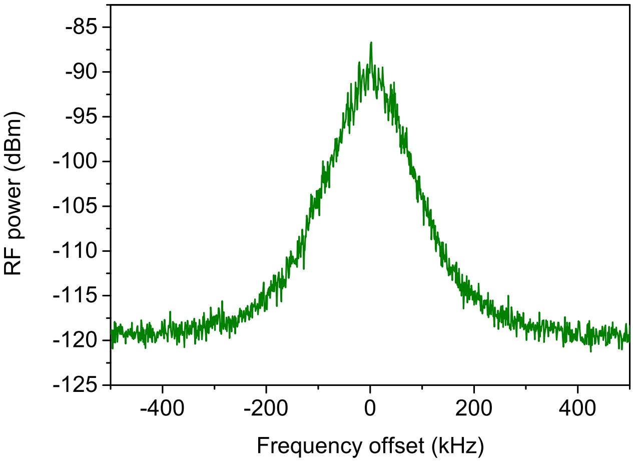

Figure 5. Measured spectrum of the beat signal showns a FWHM spectral width of 48 kHz, corresponding to a laser linewidth of 24 kHz

the refractive index of the fiber, this length should be sufficiently long to measure laser linewidths down to 10 kHz. A subsequent acousto-optic modulator shifts the light frequency by 80 MHz for generating a non-zero-frequency beating. The beat signal is detected with a photo diode connected to a radio frequency (RF) analyzer. The RF spectrum shown in Fig.5 is obtained under the same condition as for recording the data in Fig.3. The full width at half maximum (FWHM) bandwidth of the RF spectrum is 48 kHz. This corresponds to a 24 kHz laser linewidth. The measured linewidth is surprisingly narrow considering the short physical length of the laser of about 4 mm. This can be largely ascribed to the low-loss external waveguide circuit, the long effective length of the MRRs and their high frequency selectivity. As a comparison, achieving similarly narrow linewidths with standard external cavity diode lasers using, e.g., a bulk optical grating, comes at the expense of a much longer cavity length in the order ten centimeters or more, which usually also requires an additional active frequency stabilization. On the other hand when considering integrated Bragg gratings (monolithic DBR or DFB laser) the effective length of the grating is usually shorter than its physical length,[17] which gives rise to a typical linewidth in the order of 1 MHz.

4. CONCLUSION

A hybrid semiconductor-glass waveguide laser has been presented and its main properties have been investigated. A maximum of 5.7 mW output power was achieved with a SMSR larger than 50 dB. The laser exhibits a broad tuning range of 46.8 nm while the spectral linewidth is as narrow as 24 kHz. This is the smallest linewidth obtained so far for any hybrid-integrated diode laser, including work based on feedback from Si waveguide MRR circuits.[11–13] Seen the low losses of glass waveguides, a further narrowing of the linewidth into the sub-KHz range might be realized with further improved mode matching together with increasing the effective length the MRRs via smaller coupling.[6] The wide freedom of choice in selecting any desired semiconductor gain material within the transparency range of glass appears of interest for exploring the described laser also in other wavelength ranges, such as for applications in gas sensing or precision metrology.

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REFERENCES

[1] Bruce, E., "Tunable lasers," *IEEE Spectrum* **39**, 35–39 (Feb 2002).

[2] Saliba, S. D. and Scholten, R. E., "Linewidths below 100 kHz with external cavity diode lasers," *Appl. Opt.* **48**, 6961–6966 (Dec 2009).

[3] Signoret, P., Myara, M., Tourrenc, J. P., Orsal, B., Monier, M.-H., Jacquet, J., Leboudec, P., and Marin, F., "Bragg section effects on linewidth and lineshape in 1.55 μm DBR tunable laser diodes," *Photonics Technology Letters, IEEE* **16**, 1429–1431 (June 2004).

[4] Faugeron, M., Tran, M., Parillaud, O., Chtioui, M., Robert, Y., Vinet, E., Enard, A., Jacquet, J., and van Dijk, F., "High-power tunable dilute mode DFB laser with low RIN and narrow linewidth," *Photonics Technology Letters, IEEE* **25**, 7–10 (Jan 2013).

[5] Leinse, A., Heideman, R. G., Hoekman, M., Schreuder, F., Falke, F., Roeloffzen, C. G. H., Zhuang, L., Burla, M., Marpaung, D., Geuzebroek, D. H., Dekker, R., Klein, E. J., van Dijk, P. W. L., and Oldenbeuving, R. M., "Triplex waveguide platform: low-loss technology over a wide wavelength range," *Proc. SPIE* **8767**, 87670E–87670E–13 (2013).

[6] Oldenbeuving, R. M., Klein, E. J., Offerhaus, H. L., Lee, C. J., Song, H., and Boller, K.-J., "25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity," *Laser Physics Letters* **10**(1), 015804 (2013).

[7] Rabus, D., Bian, Z., and Shakouri, A., "A GaInAsP-InP double-ring resonator coupled laser," *Photonics Technology Letters, IEEE* **17**, 1770–1772 (Sept 2005).

[8] Chung, Y., Kim, D.-G., and Dagli, N., "Widely tunable coupled-ring reflector laser diode," *Photonics Technology Letters, IEEE* **17**, 1773–1775 (Sept 2005).

[9] Morichetti, F., Melloni, A., Martinelli, M., Heideman, R., Leinse, A., Geuzebroek, D., and Borreman, A., "Box-shaped dielectric waveguides: A new concept in integrated optics?," *Journal of Lightwave Technology* **25**, 2579–2589 (Sept 2007).

[10] Vlasov, Y. and McNab, S., "Losses in single-mode silicon-on-insulator strip waveguides and bends," *Opt. Express* **12**, 1622–1631 (Apr 2004).

[11] Hulme, J. C., Doylend, J. K., and Bowers, J. E., "Widely tunable vernier ring laser on hybrid silicon," *Opt. Express* **21**, 19718–19722 (Aug 2013).

[12] Suzuki, K., Kita, T., and Yamada, H., "Wavelength tunable laser diodes with Si-wire waveguide ring resonator wavelength filters," *Proc. SPIE* **7943**, 79431G–79431G–7 (2011).

[13] Nemoto, K., Kita, T., and Yamada, H., "Narrow-spectral-linewidth wavelength-tunable laser diode with Si wire waveguide ring resonators," *Applied Physics Express* **5**(8), 082701 (2012).

[14] Bauters, J., Heck, M. J. R., John, D., Tien, M.-C., Li, W., Barton, J., Blumenthal, D., Bowers, J., Leinse, A., and Heideman, R., "Ultra-low-loss single-mode Si_3N_4 waveguides with 0.7 dB/m propagation loss," 1–3 (Sept 2011).

[15] Nakamura, A., "LGLC tunable laser with highly stable smsr against large filter deviation for full C-band operation," in [*Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*], *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013* , OTh3I.6, Optical Society of America (2013).

[16] Jin, J., Wang, L., Yu, T., Wang, Y., and He, J.-J., "Widely wavelength switchable V-coupled-cavity semiconductor laser with ∼40 dB side-mode suppression ratio," *Opt. Lett.* **36**, 4230–4232 (Nov 2011).

[17] Liu, B., Shakouri, A., and Bowers, J., "Passive microring-resonator-coupled lasers," *Applied Physics Letters* **79**, 3561–3563 (Nov 2001).