Coupled cavity laser based on anti-resonant imaging via multimode interference

Citation for published version (APA):

Document license:
TAVERNE

DOI:
10.1364/OL.40.000653

Document status and date:
Published: 01/01/2015

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Coupled cavity laser based on anti-resonant imaging via multimode interference

D. D’Agostino,* D. Lenstra, H. P. M. M. Ambrosius, and M. K. Smit
COBRA Research Institute, Photonic Integration Group, Den Dolech 2, Eindhoven, 5600MB Eindhoven, The Netherlands

*Corresponding author: d.dagostino@tue.nl

Received October 21, 2014; accepted December 8, 2014; posted January 9, 2015 (Doc. ID 225345); published February 13, 2015

We report the experimental demonstration of two coupled laser cavities via self-imaging interference in a multimode waveguide. The coupling is optimized by considering images formed by two coherent phase-delayed signals at the input of a 3 × 3 splitter. As a result, the complex transfer coefficients of the coupling element can be chosen to increase the mode selectivity of the coupled system. A demonstration is given by the successful fabrication of a tunable laser with a side-mode suppression ratio (SMSR) up to 40 dB and a 6.5 nm tuning range. The laser delivers milliwatts of output power to a lensed fiber and is fully compatible with processes supporting vertically-etched sidewalls. © 2015 Optical Society of America

OCIS codes: (140.3600) Lasers, tunable; (250.3140) Integrated optoelectronic circuits; (250.5960) Semiconductor μ are complex numbers, designed

Recent progress in III–V foundry processes has enabled access to photonic integrated circuits (PICs) for a wide range of applications [1]. The monolithic integration of passive and active components with high densities allows for complex circuits with a steadily increasing number of components [2,3]. Tunable sources can be integrated into the PIC by the fabrication of a grating or by the design of a wavelength-selective tunable circuit. The first requires high lithographic resolution and additional epitaxial growth. Prominent examples are the digital super-mode distributed feedback laser [4], the grating Y-branch laser [5], and distributed feedback laser arrays [6]. Wave-length-selective circuits can be designed by combining optical filters on a chip. The resulting lasers, however, are too spacious, and suffer from an additional insertion loss, the amount of which is determined by the number of filter stages. Two examples are AWG lasers [7] and ring-filtered lasers [8]. Alternatively, single-mode lasing can be achieved by coupling two laser cavities. The theoretical foundation was developed in the 1980s, with a variety of experimentally demonstrated coupling schemes based on serially [9,10] and laterally coupled lasers [11]. The need for the precise control of the coupling coefficients, with strict fabrication tolerances, resulted in poor mode selectivity and reproducibility. Recently, a number of coupled-cavity lasers (CCLs) with telecom-compatible side-mode suppression ratios (SMSR) have been reported. These lasers use half-wave multimode interference (MMI) devices without imaging properties [12,13]. These devices were demonstrated on a nontransparent substrate, which is incompatible with PICs, which generally obtain functionality due to passive optical filters.

This work reports an active–passive integrated CCL, which is coupled via self-imaging. The coupling is achieved by means of a novel 2-Port reflector derived from a 3 × 3 MMI device, which is based on general interference. An experimental demonstration is given by the characterization of a first prototype fabricated in a commercially available foundry process [2]. The laser can be tuned via the integrated transparent phase sections over 6.5 nm, and has a SMSR up to 40 dB. Full integration into a PIC is realized with multimode interference reflectors (MIRs), which are readily available on-chip reflectors [14].

The fabricated device is schematically depicted in Fig. 1. Two Fabry–Perot cavities of different lengths, each containing an amplifier and a phase-tuning section, are coupled through a 2-Port MIR. The MIR with reflectivity R2 determines the amplitude coupling coefficients C2 and Cbar. Cx and Cbar are complex numbers, designed to have a cross-coupling value of a few percent with a relative phase of 180°. The detuning values were chosen according to previous theoretical [15] and experimental [12,13] results that predict SMSR in the 40 dB range for C2 bar ≈ 0.8 and Cx ≈ 0.2ejπ.

The laser is fabricated in a commercial InP foundry, together with other designs on a shared wafer [2]. It is based on a InGaAsP/InP multiple quantum well structure, which is monolithically integrated with transparent ridge waveguides based on a 500 nm bulk InGaAsP with Q (1.25). The cavities are 1229 μm and 1169 μm long, and each contains a 500 μm semiconductor optical amplifier (SOA) and 250 μm Q (1.25) phase-tuning section. The contact isolation is formed by removing the P-doped cladding of the waveguides over a length of 30 μm. The combined free spectral range (FSR) of the device is 4.8 nm and is determined by the Vernier effect established between the two cavities of different lengths. The final device in Fig. 2 is partially deeply etched to enhance the index contrast. This reduces the bending radii of the curves, and is essential to establish the integrated mirror

Fig. 1. Schematic of fabricated laser, with a reflective 2-port MIR. Cx and Cbar denote the complex amplitude coupling coefficients between the cavities.
of the mirror as a function of the width of the MMI. The lowest insertion loss is consequently achieved for anti-resonant input. Inside the CCL geometry, this property will automatically lead to the optimization of the laser operation. In this work, we employ a 6-μm-wide and 25-μm-long reflector.

For input signals $P_{1}^{in}$ and $P_{2}^{in}$ with differing amplitude and a fixed-phase difference of 180°, a residual image is obtained at the position of the middle waveguide. We estimate the excess loss $L$ of the mirror as a function of the input power ratio $R = P_{2}^{in}/P_{1}^{in}$ with two-dimensional finite-difference time-domain (FDTD) simulations. The excess loss $L$ for the corresponding port $N$ is defined using the result for $R = 1$ as a reference for $L = 10 \log (P_{N}^{out}/P_{N}^{in}) |_{R=1}/(P_{N}^{out}/P_{N}^{in}) |_{R=1}$. As shown in Fig. 4, the excess loss is minimized for the symmetric injection and light is lost if the intensities differ. Positive values for $L$ can be expected for asymmetric excitation. The reflection one cavity experiences does therefore effectively increase. The overall efficiency can be increased by closing one cavity with a coating, or by using an integrated reflector with high reflectivity. Consequently, the current levels for $R \approx 1$ will be reduced.

For our experiments, the laser was mounted on a copper submount with a thermo-electric cooler controlled at 15°C. The electrodes are biased with independent current sources under continuous wave (CW) operation. When 18 mA are injected into each SOA, the device reaches threshold. The emitted power of the laser varies for the asymmetric injection currents, which follows from the interference mechanism described above. A demonstration is given by taking light–current (LI) curves with an asymmetric current injection, as shown in the schematic of Fig. 5(a). Here, light is collected from SOA 1, and the current is kept constant for SOA 2 and varied for SOA 1. The LI has a typical laser diode
response, with the maximum of 5 mW for the symmetric injection of 100 mA into each SOA. If the current in SOA 2 is reduced to 30 mA, the maximum extracted power drops from 5 to 3.7 mW, indicating an additional mirror loss of 1.3 dB.

Figure 5(b) shows the complementary experiment, where the current of SOA 1 is fixed and the current of SOA 2 is altered. In this scenario, the collected power changes only as the mirror reflectivity changes. At first, SOA 1 determines the power, but with the increasing current in SOA 2, its threshold point is overcome and the mirror reflection increases until the power at the inputs of the reflector are equal. Hereafter, the effective reflection might marginally increase due to a net flow of light from SOA 2 to SOA 1. Both experiments shown in Fig. 5 indicate a decreasing threshold for increasing constant currents.

A typical single-mode spectrum at a current injection of 50 mA is shown in Fig. 6. The longitudinal mode has been selected using the integrated phase shifters. The SMSR is close to 40 dB for both the adjacent longitudinal mode and the competitor separated by one FSR. The SMRS can be further increased by increasing the difference in cavity length. This, however, reduces the tuning range. A larger tuning range can be achieved by reducing the device footprint.

We measured the SMSR of the laser for various SOA currents. The spectra are displayed in Fig. 7(a), with the corresponding SMSR plotted in Fig. 7(b). The SMSR is fitted based on Koch and Koren [15], with good agreement. The measurements indicate a red shift of the laser, which is related to the heat generation under current injection. At 69 mA injection current, we see a jump to the adjacent FSR. For higher currents, the mode competitions between the FSRs prevent a stable single-mode operation.

Tuning experiments have been performed for symmetric injection into the SOAs and by operating the phase sections in turns. The results for the injection currents from 30 to 50 mA are given in Fig. 8. We recognize digital
tuning which is typical for the Vernier filter. Mode hop instabilities occur only for the edge channels, when the device switches between the FSRs. With increasing SOA current, the broadening of the gain profile leads to competition between the FSRs. The S-type tuning curve of the laser is determined by the employed Q(1.25) guiding layer. The induced phase shift due to the carrier injection is limited, and counteracted by the thermal phase shift. As a result, an effective phase shift is only obtained above a 10 mA tuning current. With a dedicated layer stack or regrowth, the tuning current can be decreased down to a few mA. The accessible channels deduced from the map in Fig. 8 are displayed in Fig. 9.

The tuning range is enhanced by the thermal shift of the gain curve, and allows for an overall 6.5 nm tuning range.

In conclusion, we have experimentally demonstrated an active–passive integrated coupled cavity laser. The coupling between the two cavities is established via the self-imaging of two phase delayed signals in a $3 \times 3$ multimode interference reflector. The coupling is proven to be tolerant against power fluctuations of the cavities, and the coupling phase is self-regulated over the operation range. The laser is simple to fabricate, is compact, and can be fully integrated with standard processes into advanced PIC designs. The SMSR of the laser is measured to be up to 40 dB, and the tuning range via the integrated phase sections is 6.5 nm. The tuning range of the device can be further enhanced without penalizing the SMSR by reduction of the footprint, which makes it an attractive alternative to grating-based lasers.

This work is part of the TULGAS project supported by IOP Photonic Devices. The authors thank SMART Photonics for the rapid fabrication of the device used.

References