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Few-Modes Locking in a Photonic Bandgap III-V on Silicon Laser

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Abstract *We demonstrate stable operation of a multimode DFB laser-based on a 1D photonic crystal cavity. The laser signal comprises three modes spaced by ~28 GHz with linewidths below 135 kHz. Under mode-locking operation, the laser beat tone is narrowed down to 20 kHz.*

Introduction

A recent theoretical study has suggested the possibility of a new mode-locking mechanism in a laser cavity with a very limited number of modes [1]. In this laser, longitudinal modes distributed as Gauss-Hermite functions interact in a substantially different way than travelling waves in ring [2] and Fabry-Perot resonators [3]. Stable and well shaped pulses are predicted to form with only a few modes. Each of these modes, therefore, carries a larger fraction of power than in laser with more modes. This is important in some applications, for instance analog radio-over-fiber systems and for more general frequency comb applications requiring two or more beating modes with narrow linewidths.

Here we design a laser cavity based on a tapered distributed feedback grating on Silicon, similar to the low-noise laser demonstrated by Santis *et al.* [4,5] Here the tapering profile is changed to allow a few equispaced modes, based on the concept of effective parabolic potential in a photonic crystal [1]. Compared with classical mode locked designs, this type of distributed feedback laser design offers design flexibility as the mode separation is no longer linked to active cavity free spectral range. Here we demonstrate a remarkably stable frequency comb over > 50 mA bias current range. Here, we demonstrate the first mode locking of an engineered photonic bandgap III-V on Silicon laser exhibiting narrow linewidth modes spaced by 28 GHz.

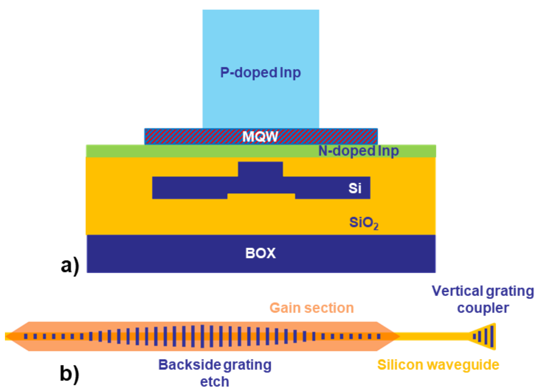

Fig. 1: a) Schematic cross-section of the laser b) simplified layout of the cavity

Device & design description

The device described in Fig 1 a) and b) is fabricated using a standard III-V on Silicon wafer bonding process [6], with a SiO_2 bonding layer as thin as 23 nm. Optical gain is obtained through 6 AlGaInAs quantum well layers. Aluminium-based quantum wells were chosen because of their higher band offset in the conduction band than Phosphide-based ones. As a result, we obtain a much better electron confinement that decreases the thermionic emission, hence making them suitable for high temperature operation [7].

In order to achieve the desired value of grating strength, the grating corrugation has been etched using a backside process developed in the CEA Leti's 300mm pilot line [8]. The resulting average grating strength is around 81 cm^{-1}. The laser is

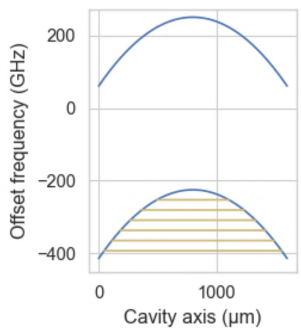

Fig. 2: Engineered photonic bandgap containing the different frequency levels.

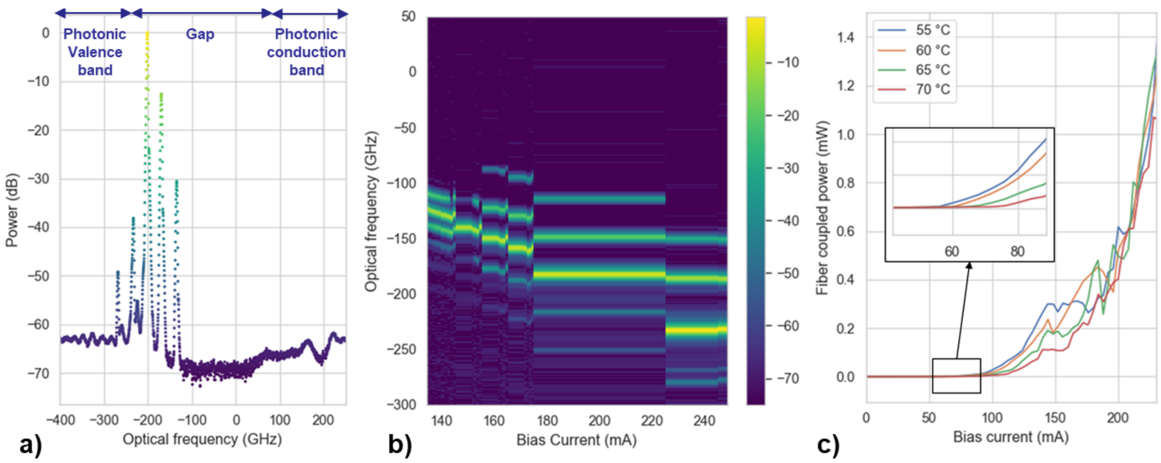

Fig. 3: a) optical spectrum at 183mA and 60°C offset frequency is relative to1564 nm b) Evolution with a 1 mA step of spectral power vs bias at 60°C the frequency offset is relative to 1564 nm c) L-I characteristic

1,6 mm long and contains two gain sections separated by an isolating hydrogen implantation zone, allowing us to have an asymetric current injection in the two halves of the laser gain medium. As previously stated, the design of the laser is inspired by Santis *et al* [4,5]. Their motivation for an engineered photonic bandgap laser was controlling the spatial field distribution in order to reduce radiative and extraction losses leading to reduced phase noise of the single-mode laser.

This work presents a completely new prototype of mode lock laser with a few Hermite-Gauss modes locking inside a parabolic photonic well-based laser cavity. It produces -by design- a very stable and fabrication resistant laser frequency comb as predicted in [9] with equally spaced modes. The parabolic photonic bandgap is illustrated in Fig.2 with the equivalent photonic valence and conduction bands and their corresponding lasing frequency levels. The frequency levels are computed from a transfer matrix simulation method (TMM) of the Bragg grating [10].

The photonic well is made by inducing a parabolic offset in the photonic valence band f_v. This offset follows the quadratic formula given in (1) with L and W respectively being the laser length and the photonic well depth.

$$f_v(\mathrm{x}) = f_0 + \mathrm{W}\left[1 - \left(\frac{2x}{L} - 1\right)\left(\frac{2x}{L} + 1\right)\right] \qquad (1)$$

with x the position along the well having its origin at the center of the cavity. The photonic valence band offset is made by reducing the mode near the center of the cavity. The index n_0 and n_1 of an (un)-perturbed waveguide region are related to f_v following formula (2), which can be obtained using the coupled mode theory from [11].

$$n_1{}^2 + n_1\left(2n_0 - 3\frac{c}{2f_v\Lambda}\right) + n_0\left(n_0 - \frac{c}{2f_v\Lambda}\right) = 0 \qquad (2)$$

with n_0, n_1, Λ, c respectively being, the transverse mode effective index in an (un)-perturbed waveguiding region, the effective index perturbation along the well, the grating period and the light celerity in vacuum. Then, computing the root of equation (1) gives the effective index pertubation n_1 along the laser cavity.

Static characteristics

All the measurements are performed above 55°C in order to align both the optical gain peak and the engineered photonic bandgap frequency levels. A DC current from a unique current source is injected on both sides of the gain section. From one of the two outputs of the laser, the optical signal is coupled to the fiber using a vertical grating coupler centered at 1545 nm and exhibiting 4,5 dB of coupling losses at that wavelength.

Figure 3 c) shows the L-I characteristic of the laser. At 60°C, the laser threshold is 60 mA. This relatively high value can be explained, in those types of laser cavity, by the low confinement factor in quantum wells (1.5 %). However low propagation and mirror losses compensate low effective gain, which results in an acceptable threshold value. Regarding the L-I curve, it needs to be stated that no power penalty is noticed in the 180 mA to 240 mA range at increasing temperature. The multimode DFB laser exhibits a fiber coupled output power of 1 mW for 230 mA bias current at a regulated temperature of 60 °C (see Fig 3 c)). The following observations were made with such bias and temperature values. Figure 3 b) illustrates the evolution of the first three modes inside the photonic well and their spectral power and distribution depending on the bias current at 60°C. The optical spectrum

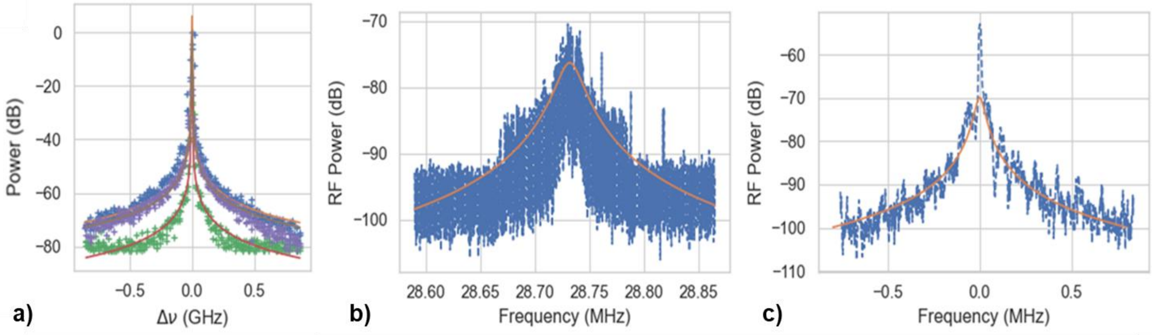

Fig. 4: a) Superposed optical spectra showing the spectral power vs lasing frequency offset of the well lasing modes. Lorentzian fit are computed to estimate their linewidth b) RF spectrum under free running operation of the laser c) RF spectrum of the mode locked laser driven by a -1 dBm power 28.3 GHz sinusoidal signal. Frequency offset is 28.3 GHz

analyser for this measurement has a standard resolution of 20 pm and the current step is 1 mA. A thermal drift of the modes' frequency is observed between 140 mA and 175 mA. Here on the other hand, a very stable frequency comb is observed when the laser is biased between 175 and 225 mA, then above 225mA. We are still investigating the physical reasons explaining this ultra-stable spectral and optical power behaviour. We can also distinguish the stopband, which is 4 nm wide and centered at 1564 nm (ie 0 GHz on the y axis). On the optical spectrum shown in Fig 3 a), the 2 lines outside of the stop band seem to be the result of a four-wave mixing between the modes of respective frequency offset -169 GHz and -200 GHz. The three laser modes inside the stopband are the ones expected to reach lasing condition since we can retrieve them from the TMM simulation of the laser cavity Fig. 2. Measuring the above threshold spectrum with a heterodyning optical spectrum analyser with a 5 MHz resolution makes it possible to estimate a maximum value for the linewidth of each mode. Fig. 4 a) shows these optical spectra and an estimation of the linewidth of each mode by fitting the spectra points in a 1.4 GHz window centered on each of the Lorentzian laser shapes. We estimated the different peaks to have respectively 110 kHz, 120 kHz and 135 kHz linewidth.

Mode spacing & mode locking

As already demonstrated before the device exhibits 3 equally spaced lasing modes. Their 28 GHz spacing is quite stable as shown by the electrical spectrum in Fig 4 b). The spectrum exhibits only one line in our electrical spectrum analyser range, which is the sign of the constant spacing of the modes. However, this (largely over-estimated) 10 MHz wide RF beat signal presents low frequency instability due to convective airflow as the chip is on a 60 °C Peltier cell in a 20°C laboratory room.

By driving one of the laser gain sections with a small power (-1 dBm) sinusoidal signal around the 28.5 GHz center frequency, it is possible to observe a stable mode locking of the laser characterised by a 20 kHz -3 dB bandwidth peak on the electrical spectrum Fig 4 c) [12]. We clearly observe a mode locking regime, excluding any gain-switching one, as the driving signal power is too small to reach threshold (RF swing of 0.16mA across the laser diode of resistance 3.46 Ω injected with 183 mA DC bias). We also observed a frequency locking range. Its amplitude depends on the RF signal power, which is -1dBm here. The unresolved very fine peak at the top of Lorentzian-shaped microwave signal on Fig 4 c) spectrum is the signature of the sinusoidal driving signal.

Conclusions and outlook

We demonstrated the stable mode locking operation of a III-V on Si multimode laser exhibiting three narrow linewidths modes spaced by ~28 GHz over a large bias current range (>50 mA). Active locking of the modes is achieved by driving one of the two laser gain sections with a -1 dBm small electrical sinusoidal signal at the 28 GHz frequency. A 20 kHz wide beat tone is observed. This flexible and fabrication proof design paves the way for future applications requiring temperature-insensitive frequency combs in a diversity of fields, spanning telecommunications and datacommunications, metrology, sensing, among others.

Further improvements of this laser structure include the use of quantum dots instead of quantum wells to enable passive mode-locking operations with a lower level of phase noise, and better insensitiveness to optical feedback [13]. In addition, a different design of the photonic bandgap would reduce modes extraction losses in order to achieve equalized power frequency comb teeth.

Acknowledgements

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