Linewidth Characterization of Integrable Slotted Single-Mode Lasers

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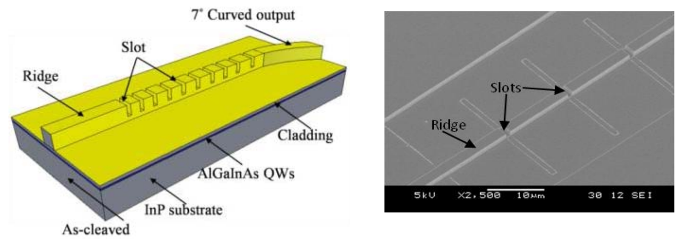
***Abstract*— A single-mode laser platform has been developed with a simple and high-yield fabrication based on etched slots. We present linewidth measurements on such lasers, which are fabricated without any regrowth steps. The group of slots placed on one side of laser cavity provides sufficient reflectivity for lasing, which allows the laser to be integrated with other devices such as semiconductor optical amplifiers and modulators. The laser with an effective cavity length of 450 μm exhibits a threshold current of 31 mA and a side-mode suppression ratio of 48 dB. The laser shows a minimum Lorentzian linewidth of ∼720 kHz at room temperature. The linewidth remains ∼1 MHz within the temperature range of 10 °C–60 °C.**

***Index Terms*— Single mode laser, surface grating, side mode suppression ratio (SMSR).**



(a) (b)

Fig. 1. (a) 3D schematic structure of the slotted laser. (b) SEM image of the etched slots.

I. Introduction

SINGLE-MODE semiconductor lasers with narrow linewidth have wide applications in fiber-optic communications, especially in coherent optical communication systems using advanced modulation formats. In the past, distributed feedback (DFB) lasers and distributed Bragg reflector (DBR) lasers have shown typical linewidth value of more than 10 MHz [1]. A lot of effort have been made to reduce the linewidth to the optimum value of about 0.5 MHz, mostly by making the laser cavity longer [2]–[4]. However, for many short cavity lasers, the linewidth remains around a few MHz [5]. The lowest linewidth of 3.6 kHz for DFB laser was demonstrated in [6], although such laser results in complex structure and fabrication. State-of-art devices such as laterally coupled DFB lasers [7], [8], and hybrid Si/III-V lasers [9] have shown narrow linewidth results suitable for coherent communications, however these are complex devices requiring high resolution processing. The laser platform used here utilizes simple fabrication methods by introducing reflective defects (slots) into a Fabry-Perot (FP) laser cavity where single-mode emission can be achieved by positioning these features at particular locations along the cavity [10], [11]. A high side-mode suppression ratio (SMSR) and narrow linewidth of these lasers were demonstrated in [11] and [12]. However, these particular lasers needed both facets to be cleaved to form the fundamental FP cavity, so they cannot be monolithically integrated with other optical components. Recently, our group has proposed a new single-mode laser design based on slots etched on one side of the laser cavity to provide sufficient reflection for lasing to occur. This type of laser can be monolithically integrated with other photonic devices. We have already demonstrated the performance of this laser with high SMSR of more than 50 dB [13]. The linewidth of such lasers was first measured in [14] using a lensed fiber coupling system. However, the back reflection from the lensed fiber coupled into the laser cavity influenced the measurement accuracy. In this letter, we present a detailed characterization of the spectral linewidth of the slotted single-mode laser using a free space coupling system which employs isolators with isolation about 60 dB to prevent any external feedback. The laser with effective cavity length of 450 μm exhibits a minimum Lorentzian linewidth around 720 kHz at 170 mA drive current at room temperature. The linewidth dependence on temperature has also been characterized. We took measurements in the temperature range between $10 \leq T \leq 60$ °C where the linewidth value remained around 1 MHz. The cavity length effect on linewidth was also checked and the extrapolation predicted that a laser with effective cavity length of about 550 μm is required to achieve the industry standard of 0.5 MHz linewidth for coherent communications.

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II. Device Structure and the Fabrication

The schematic structure of the slotted single-mode laser is shown in Fig. 1(a). The laser has a 2 μm wide surface ridge waveguide which has the same epitaxial structure as in [13].

The structure consists of an active region of 5 AlGaInAs quantum wells with photoluminescence peak (PL) near 1530 nm. A 1.6 μm-thick p-doped InP material, a 50 nm p-doped InGaAsP and a 200 nm InGaAs contact layer are above the active region. One side of the laser cavity has multiple slots which act as an active DBR of the laser to provide enough reflection for lasing to occur. The output of the laser is curved to 7 degrees to reduce reflections from the front facet. The laser has a single contact which covers the area with and without slots. The laser operates using reflection from the slots at the front and the cleaved facet at the back to achieve single mode operation, so the slot parameters such as slot depth, width, period and number need to be optimized in the design. For optimization, the 2-D scattering matrix method was used [15]. From the analysis it was calculated that a group of 24 slots with slot depth of 1.35 μm and period 8.96 μm are suitable to provide sufficient reflectivity with a narrow bandwidth while keeping the cavity length short. The slot width was set to 1.1 μm which makes the laser compatible with standard photolithography although the laser studied here used e-beam lithography to define slots in this initial study. The slot depth and width from the fabrication is around 1.33 μm and 1.02 μm, respectively from the SEM image which is shown in Fig. 1(b), both parameters being a little less than designed. The device was fabricated using a two-step dry etching process which is described in [13]. The ridge was etched to a height of 1.85 μm. The slot depth was about 0.5 μm shallower than the ridge. The total cavity length of the laser is 750 μm where 335 μm is the length between the back facet and the first slot (non- slotted region), with a 215 μm long slot section and a 200 μm region for the curved front section. After the ridge was passivated and metal contacted, the laser bars were cleaved and mounted on silicon carriers for testing.

III. Linewidth Characteristics

The devices were placed on a copper heat sink which was then loaded on a thermoelectric cooling (TEC) controller to keep the temperature constant. The fabricated device was tested under continuous-wave (CW) operation at room temperature. For the 750 μm long laser (effective cavity length around 450 μm) the threshold current (I_{th}) was measured to be 31 mA with a slope efficiency of about 0.11 mW/mA at a drive current of 100 mA. The lasing peak is at 1546.2 nm as shown in the inset of Fig. 3. As we have distributed mirror due to the slots, we use an effective cavity length for our laser. The mode spacing is 0.84 nm, inset of Fig. 3, and it can be used to determine the effective cavity length. This length can be extracted using the mode spacing from the equation $\Delta\lambda = \lambda_o^2/(2n_g L_{eff})$ where $\Delta\lambda$ is the mode spacing, n_g is group refractive index, λ_o is the lasing peak and L_{eff} is effective cavity length. From the equation we found L_{eff} to be 406 μm with $n_g = 3.5$. Assuming that the scattering loss resulted from the slots is compensated by the gain, the penetration depth into the slot region is calculated as 107 μm using the equation $1/2\kappa \tanh(\kappa L_g)$ [16], where κ is the coupling constant and L_g is the length of the slotted section. Combined with the non-slotted region an effective cavity length of 442 μm is predicted which is slightly over-estimated compared with the value extracted from the mode spacing. This might mean that the loss from the practically fabricated slots is higher than estimation. The measured SMSR is about 48 dB at 100 mA ($I \sim 3I_{th}$). The measured light-current (L-I) curve and laser spectrum are similar to those in [13].

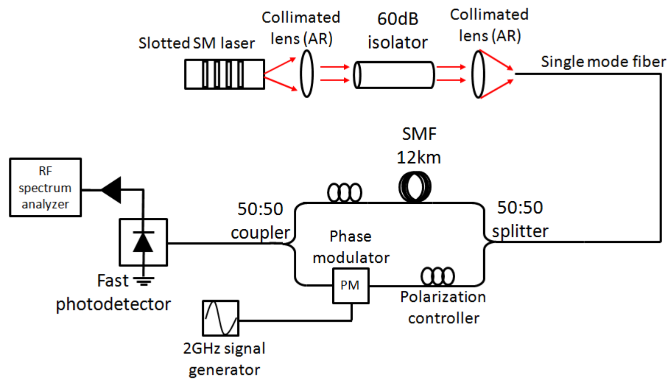

Fig. 2. Experimental setup of DS-H technique.

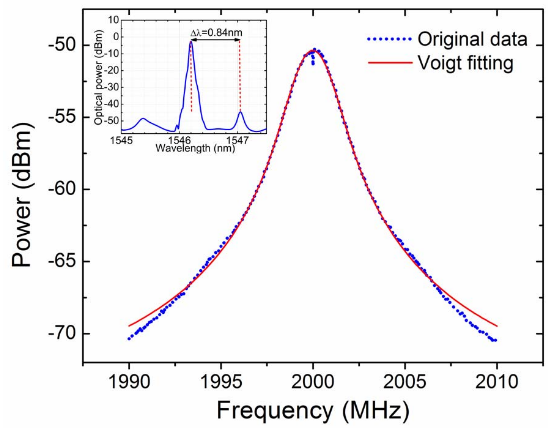

Fig. 3. Measured electrical spectrum on log scale of a slotted single-mode laser fitted by a Voigt function. Inset shows measured optical spectrum at 100 mA.

For the linewidth characterization the delayed self-heterodyne technique (DS-H) [17] was used which is shown in Fig. 2. Because we are dealing with unpackaged bare devices it is important to have sufficiently high isolation to avoid any back reflections. For this reason a free-space setup was used where two anti-reflection (AR) coated collimation lenses and a 60 dB isolator are employed to collimate the laser beam and minimize any back reflection to the laser cavity.

The collimated laser beam is then focused through another AR coated lens into a single-mode (SM) fiber and split into two paths. One goes through 12 km of single mode fiber which corresponds to a 60 μs time delay and the second is modulated by a $LiNbO_3$ phase modulator to shift the signal to 2 GHz to increase the measurement accuracy. A polarization controller maintains the beam polarization. A 50:50 coupler combines the two beams and the mixed signal is sent to a fast photodetector. Then the linewidth spectrum is recorded using an electrical spectrum analyzer (ESA). The resolution bandwidth of the ESA was set to 30 kHz.

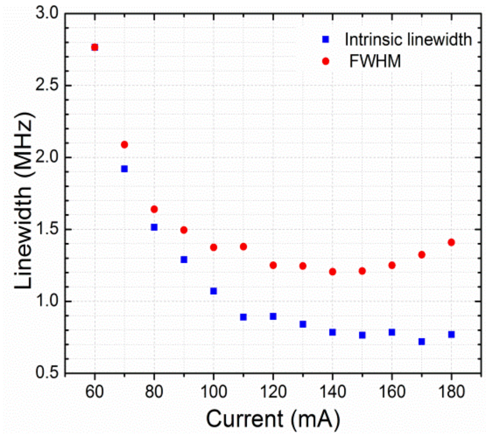

Fig. 4. Lorentzian linewidth and FWHM as a function of injection current. The red dots indicate measured linewidth and blue squares indicate Lorentzian linewidth.

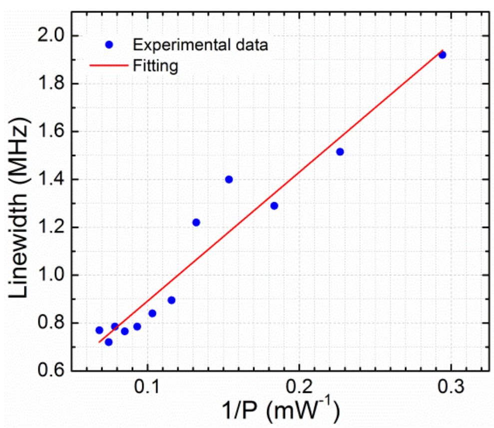

Fig. 5. Lorentzian linewidth dependence on inverse output power.

Fig. 3 shows the measured spectrum of a slotted laser using the ESA. The blue dots represent the original data which was collected using the ESA and red line is a Voigt fitting. The dip at the centre is the artifact from the measurements. We measured the spectrum at different currents and in all of them we found such a dip. The Gaussian contribution to the linewidth comes from noise sources not associated with the laser linewidth. We perform the deconvolution to extract the Lorentzian contribution associated with the laser itself. The spectrum is well fitted with a Voigt function [18] which is a convolution of Lorentz and Gaussian profiles. The Lorentzian linewidth is 840 kHz at an injection current of 130 mA which is realized by using an ultra low noise current source. The linewidth measurements were measured using this low noise current source in the free-space setup in comparison with standard current sources which we used in our previous results [14].

The well-known Schawlow-Townes formula modified by Henry [19], expresses the linewidth as being inversely proportional to the output power. In Figs. 4 and 5 this behavior was verified; the linewidth of slotted laser was measured between 60 and 180 mA at room temperature. It is clearly seen that a dramatic decrease of linewidth occurs by increasing the number of carriers injected into the system. The lowest

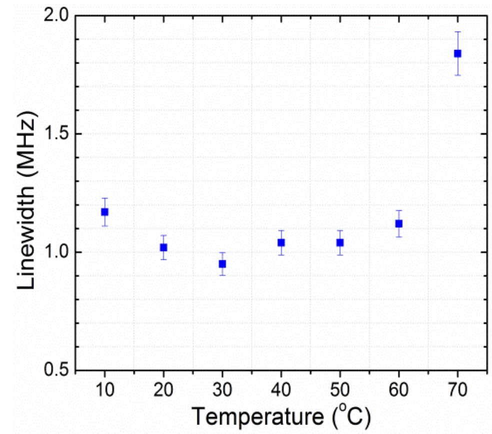

Fig. 6. Lorentzian linewidth dependence on temperature between 10 to 70 °C.

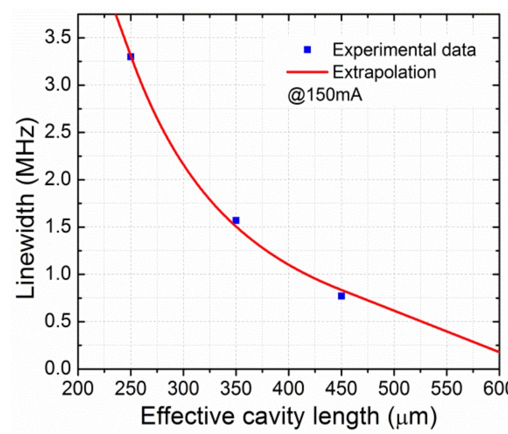

Fig. 7. Measured Lorentzian linewidth values for different cavity lengths.

linewidth value of 720 kHz was obtained at 170 mA. As found in [18], the technical noise has a Gaussian profile and at the highest current values the Gaussian contribution is greater than the intrinsic linewidth with a Lorentzian profile.

Fig. 5 shows the linewidth dependence on inverse output power which was obtained by converting input current to output optical power.

The linewidth dependence on temperature was also measured. The laser was set to 130 mA, several times the threshold current (I_{th}-31 mA). Results show that temperature has a negligible influence on the linewidth within the temperature range from 10 to 60 °C and the linewidth remains around 1 MHz as is shown in Fig. 6. However, at 70 °C the laser output power dropped due to increased heat generation in the device. Moreover because the measurements were done with unpackaged devices and on a copper heat sink, this leads to a poor heat dissipation which in turn will affect the broadening of the linewidth as is shown in Fig. 6.

We also observed the effect of cavity length on the linewidth. Lasers with shorter effective cavity length of about 250 and 350 μm were also measured. The longer cavity length shows a narrower linewidth, which is demonstrated in Fig. 7. The extrapolation shown in Fig. 7 indicates that a laser with effective cavity length of only 550 μm is required to achieve the industry standard of a laser with 0.5 MHz linewidth for coherent communications.

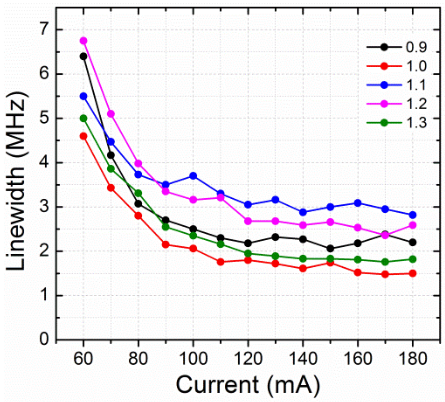

Fig. 8. Lorentzian linewidth as a function of injection current for lasers with different slot width from 0.9 to 1.3 μm.

The last characterization was done to see how slot parameters will affect the linewidth. For this, lasers with different slot width, i.e 0.9, 1.0, 1.1, 1.2, 1.3 μm and with effective cavity length of 350 μm were measured. From the simulations in [15] a variation of slot width (± 0.1 μm) does not affect the laser threshold current. The slot width also does not have a strong effect on the linewidth either as shown in Fig. 8. From the figure the overall trend is the same as in Fig. 4 and the linewidth for different lasers varies between 1.5 and 3 MHz at the highest current. We need to have a large set of lasers with different slot widths and depth to obtain a clear picture of the effects of slot parameters on the linewidth.

IV. Conclusion

In summary, we have presented detailed spectral linewidth measurements of slotted single-mode lasers. First, the laser with an effective cavity length of 450 μm was measured, which maintain stable single-mode operation with an SMSR near 50 dB. The lowest Lorentzian linewidth of 720 kHz was obtained at an injection current of 170 mA at room temperature. The changes in temperature show little effect on the linewidth which remains around 1 MHz between 10 to 60 °C. For comparison the lasers with effective cavity lengths of 250 and 350 μm were also measured and results show that the linewidth is inversely proportional to the effective cavity length. From this it is predicted that a 550 μm effective cavity length is needed to obtain a 500 kHz Lorentzian linewidth. The main advantage of these lasers is the simple fabrication where potentially standard photolithography can be used. Thus, such a laser platform with narrow linewidth has strong potential for applications in coherent communications.

References

[1] I. D. Henning, L. D. Westbrook, A. W. Nelson, and P. J. Fiddyment, "Measurements of the linewidth of ridge-guide DFB lasers," *Electron. Lett.*, vol. 20, no. 21, pp. 885–887, Oct. 1984.

[2] S. Ogita, Y. Kotaki, M. Matsuda, Y. Kuwahara, and H. Ishikawa, " Long-cavity multiple-phase-shift distributed feedback laser diode for linewidth narrowing," *J. Lightw. Technol.*, vol. 8, no. 10, pp. 1596–1604, Oct. 1990.

[3] M. Okai, T. Tsuchiya, K. Uomi, N. Chinone, and T. Harada, "Corrugation-pitch-modulated MQW-DFB laser with narrow spectral linewidth (170 kHz)," *IEEE Photon. Technol. Lett.*, vol. 2, no. 8, pp. 529–530, Aug. 1990.

[4] S. Ogita, Y. Kotaki, K. Kihara, M. Matsuda, H. Ishikawa, and H. Imai, "Dependence of spectral linewidth on cavity length and coupling coefficient in DFB laser," *Electron. Lett.*, vol. 24, no. 10, pp. 613–614, May 1988.

[5] H. Ishii, K. Kasaya, H. Oohashi, Y. Shibata, H. Yasaka, and K. Okamoto, "Widely wavelength-tunable DFB laser array integrated with funnel combiner," *IEEE J. Sel. Topics Quantum Electron.*, vol. 13, no. 5, pp. 1089–1094, Sep./Oct. 2007.

[6] M. Okai, M. Suzuki, and T. Taniwatari, "Strained multiquantum-well corrugation-pitch-modulated distributed feedback laser with ultranarrow (3.6 kHz) spectral linewidth," *Electron. Lett.*, vol. 29, no. 19, pp. 1696–1697, Sep. 1993.

[7] L. Hou, M. Haji, J. Akbar, and J. H. Marsh, "Narrow linewidth laterally coupled 1.55 μm AlGaInAs/InP distributed feedback lasers integrated with a curved tapered semiconductor optical amplifier," *Opt. Lett.*, vol. 37, no. 21, pp. 4525–4527, Nov. 2012.

[8] J. Telkkala *et al.*, "Narrow linewidth laterally-coupled 1.55 μm DFB lasers fabricated using nanoimprint lithography," *Electron. Lett.*, vol. 47, no. 6, pp. 400–401, Mar. 2011.

[9] C. T. Santis, S. T. Steger, Y. Vilenchik, A. Vasilyev, and A. Yariv, "High-coherence semiconductor lasers based on integral high-Q resonators in hybrid Si/III–V platforms," *Proc. Nat. Acad. Sci. United States Amer.*, vol. 111, no. 8, pp. 2879–2884, Feb. 2014.

[10] B. Corbett and D. McDonald, "Single longitudinal mode ridge waveguide 1.3 μm Fabry–Pérot laser by modal perturbation," *Electron. Lett.*, vol. 31, no. 25, pp. 2181–2182, Dec. 1995.

[11] Y. Wang, Y. Yang, S. Zhang, L. Wang, and J.-J. He, "Narrow linewidth single-mode slotted Fabry–Pérot laser using deep etched trenches," *IEEE Photon. Technol. Lett.*, vol. 24, no. 14, pp. 1233–1235, Jul. 15, 2012.

[12] B. Kelly *et al.*, "Discrete mode laser diodes with very narrow linewidth emission," *Electron. Lett.*, vol. 43, no. 23, pp. p. 1282–1284, Nov. 2007.

[13] W.-H. Guo *et al.*, "Integrable slotted single-mode lasers," *IEEE Photon. Technol. Lett.*, vol. 24, no. 8, pp. 634–636, Apr. 15, 2012.

[14] Q. Lu *et al.*, "Two-section single-mode lasers based on slots suitable for photonic integration," *Electron. Lett.*, vol. 48, no. 15, pp. 945–946, Jul. 2012.

[15] Q. Lu, W.-H. Guo, D. Byrne, and J. F. Donegan, "Design of slotted single mode lasers suitable for photonic integration," *IEEE Photon. Technol. Lett.*, vol. 22, no. 11, pp. 787–789, Jun. 1, 2010.

[16] L. A. Coldren and S. W. Corzine, *Diode Lasers and Photonic Integrated Circuits*. Hoboken, NJ, USA: Wiley, 1995.

[17] T. Okoshi, K. Kikuchi, and A. Nakayama, "Novel method for high resolution measurement of laser output spectrum," *Electron. Lett.*, vol. 16, no. 16, pp. 630–631, Jul. 1980.

[18] S. Spießberger, M. Schiemangk, A. Wicht, H. Wenzel, O. Brox, and G. Erbert, "Narrow linewidth DFB lasers emitting near a wavelength of 1064 nm," *J. Lightw. Technol.*, vol. 28, no. 17, pp. 2611–2616, Sep. 1, 2010.

[19] C. H. Henry, "Theory of the linewidth of semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 18, no. 2, pp. 259–264, Feb. 1982.