A Monolithic MQW InP/InGaAsP-Based Optical Comb Generator

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***Abstract*— We report the first demonstration of a monolithic optical-frequency comb generator. The device is based on multi - section quaternary/quaternary eight-quantum-well InP/InGaAsP material in a Frequency Modulated (FM) laser design. The modulation is generated using quantum confined Stark effect phase-induced refractive index modulation to achieve fast modulation up to 24.4 GHz. The laser was fabricated using a single epitaxial growth step and quantum well intermixing to realize low-loss phase adjustment and modulation sections. The output was quasi continuous wave with intensity modulation at less than 20% for a total output power of 2 mW. The linewidth of each line was limited by the linewidth of the free running laser at an optimum of 25 MHz full width half maximum. The comb generator produces a number of lines with a spacing exactly equal to the modulation frequency (or a multiple of it), differential phase noise between adjacent lines of -82 dBc/Hz at 1 kHz offset (modulation source limited) and a potential comb spectrum width of up to 2 THz (15 nm), though the comb spectrum was not continuous across the full span.**

***Index Terms*— Optical frequency comb generation, Laser diode, FM laser.**

I. Introduction

Many different applications, ranging from dense wavelength division multiplexed (WDM) optical communications [1] to photonic THz synthesis [2-4] require a reliable and cost-effective frequency reference source. The most reliable source as frequency reference are atomic or molecular resonances [5,6]. They also offer a large number of frequency lines in relatively dense grid [7,8], However, they are not suitable for integrated systems. Several other solutions have been proposed to provide a regularly spaced frequency comb, such as a Fabry-Perot interferometer [9] or a fibre ring resonator [10], both of which can offer a large frequency comb span. The frequency accuracy and stability of these devices compared to the atomic or molecular resonances are limited by the optical length of the resonators, and their mechanical stability (sensitivity to vibration and thermal changes), though they could be stabilised by locking them on an atomic or molecular transition. Another solution is the use of deep angle modulation of an optical source to generate precisely spaced frequency lines [11,12]. Such systems can be reasonably compact and provide lines over a 4 THz (-50 dB bandwidth) span [12]. However the power of each line is small (from 10 μW/line at the seed laser peak down to 1 nW/line 3 THz from the peak) and the number of frequency lines and their spacing are limited by the difficulty of realizing such modulation at high frequency. Ultra wide frequency comb generators (30 THz) have also been demonstrated by further increasing the comb width using self-phase modulation in an optical fibre [13]. Other solutions such as an amplified fibre loop comb generator [14,15] or mode locked semiconductor lasers [16-18] can offer hundreds of lines with a spacing from 10 to 25 GHz over a band of at least 1THz with a stability limited by the thermal stability of the semiconductor laser (master laser in the case of the fibre loop).

The principle of the FM laser [19] is an extension of the FM mode-locked laser solution and should offer a large number of equally spaced frequency lines, spaced by the modulation source frequency, over the gain spectrum of the semiconductor laser, but without the strong intensity modulated envelope and the critical frequency tuning of a mode-locked laser which is detrimental to some filtering schemes. In this paper we describe such a monolithic InP/InGaAsP FM laser optical comb generator using the Quantum Confined Stark Effect (QCSE) [20] as the refractive index modulation mechanism. The laser described in this paper provides a few comb lines spaced by 24.4 GHz over a non-continuous 15 nm wavelength (2 THz) span. It shows stable performance and an almost constant output power of up to 2 mW (an average of 20 μW/line, as the number of lines is limited). Furthermore, the phase noise generated when heterodyning two successive lines was limited by the phase noise of the modulation source used, and the linewidth of each line created was equal to the free-

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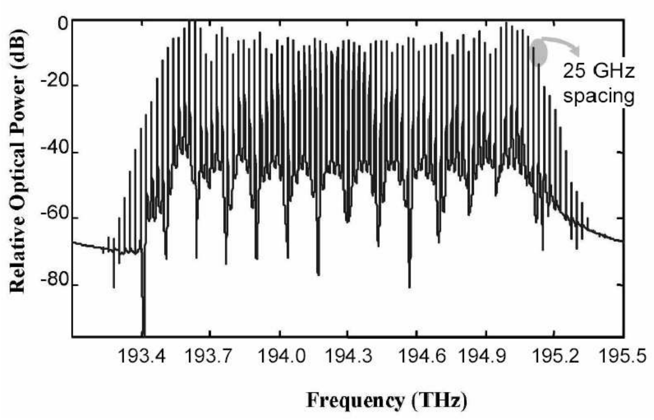


Fig. 1: Theoretical spectrum of an FM laser.

running laser linewidth. The different issues related to the fabrication of this laser, and some of the operation limitations will also be discussed.

II. Principle of the FM Source

FM laser operation occurs when the laser cavity phase is modulated at a frequency close to the axial frequency [19]. In ideal FM laser operation, there is frequency modulation and no intensity modulation, and the spectrum will comprise a number of lines spaced by the modulation frequency depending on the frequency detuning from the axial mode and the amplitude of the modulation. When the modulation frequency is equal to the axial frequency the laser will transfer to a mode-locked pulse regime [21]. The FM laser regime is generated by the phase modulation which induces coupling between the different modes of the cavity. The resulting spectrum can be described by the following equations:

$$E(t) = E_0 \sum_{n=-\infty}^{\infty} J_n(\Gamma) e^{j(\omega_0 + n\omega_m)t} \quad (1),$$

$$\Gamma = \frac{\Delta\Phi}{2\pi} \frac{\omega_{ax}}{|\omega_{ax} - \omega_m|} \quad (2).$$

In these equations E_0 is the amplitude of the optical field, ω_0 is the laser operating frequency, ω_m is the modulation frequency, ω_{ax} is the axial mode spacing of the Fabry-Perot cavity, $\Delta\Phi$ is the amplitude of the phase modulation and J_n is an ordinary Bessel function. Note that these equations represent an ideal laser with a flat gain spectrum and pure single mode operation (the fundamental mode is described as a Dirac function). This perfect theoretical laser will generate a spectrum as shown in Figure 1. To represent a more realistic laser one can introduce a Lorentzian function to describe the laser operating mode linewidth and simulate what will happen if this laser has several modes operating at the same time (free running) by summing the FM spectra of each mode. Considering the approximations mentioned above, equation (1) can be rewritten as:

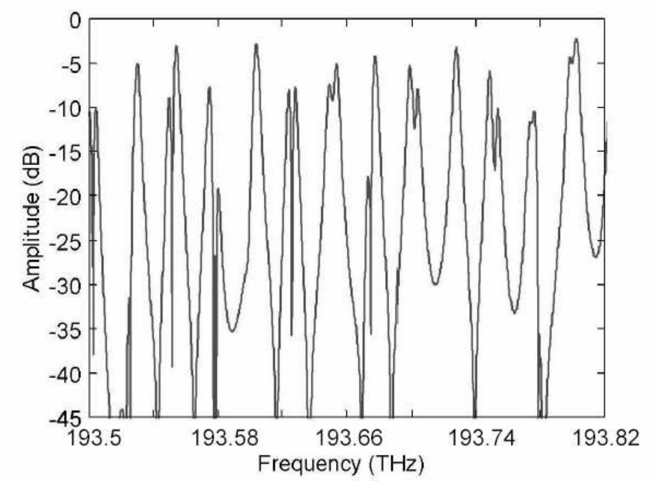


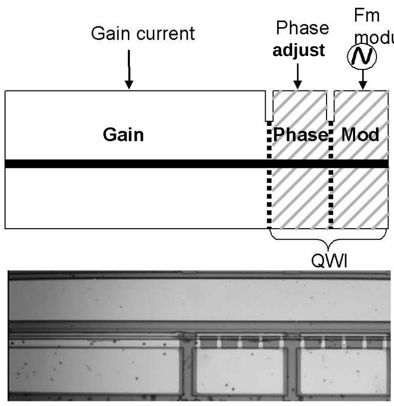
Fig. 3: Theoretical comb spectrum generated by a multimode laser.

$$E(t) = \sum_{l=0}^{K} E_0 \sum_{n=-\infty}^{\infty} L_w(\omega - (\omega_l + n\omega_m)) J_n(\Gamma) \cdot \ldots \quad (3),$$
$$\ldots e^{j(\omega_l + n\omega_m)t}$$

Where $L_w(\omega)$ is a Lorentzian function where the mode linewidth is w, and we have a total number of K modes operating in the laser cavity. Note that equation (2) remains the same. Figure 2 shows a selection of lines created by the FM modulation when 3 modes are operating in the cavity. As expected the lines are broader, as they are a superimposition of the different FM created lines from each of the free running modes. Furthermore, as the spacing of the FM comb and the spacing of the free-running laser modes are slightly different, the linewidth of each resulting comb line will depend on its distance from the free running laser modes. Therefore for optimum operation the FM laser should exhibit single mode operation in the free-running mode (i.e. when not modulated).

III. Description of the Laser

Figure 3 (left) shows a schematic of the three section laser. The laser was 1.85 mm long (~25 GHz axial mode spacing) with 170 μm long modulation and phase sections. The phase section was used to change the axial mode spacing and thus



p-InGaAs	200 nm
p-InP	1400 nm
p-InGaAsP Q1.3	30 nm
p-InP	170 nm
InGaAsP Q1.3	10 nm
8 x InGaAsP Q1.65 wells (+1% strain)	7 nm
& 7 x InGaAsP Q1.3 barriers (-0.5% strain)	14 nm
InGaAsP Q1.3	10 nm
n-InP	1500nm
Semi-insulating InP substrate	

Fig. 2: Schematic and optical micrograph of the three section laser (left) and epitaxial structure (right).

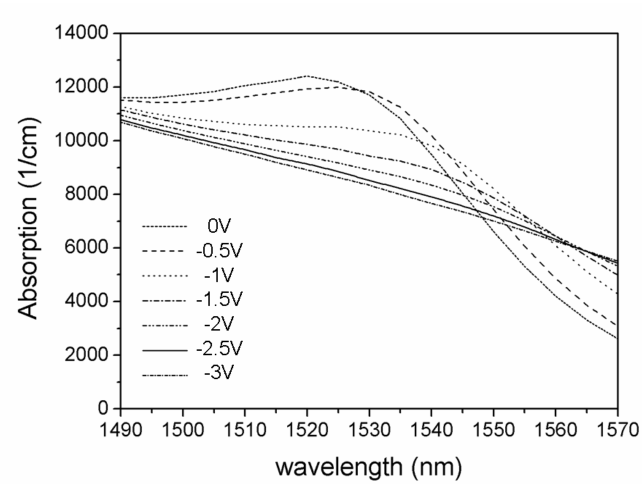


Fig. 4: Absorbtion changes as a function of reverse bias for the propagating mode.

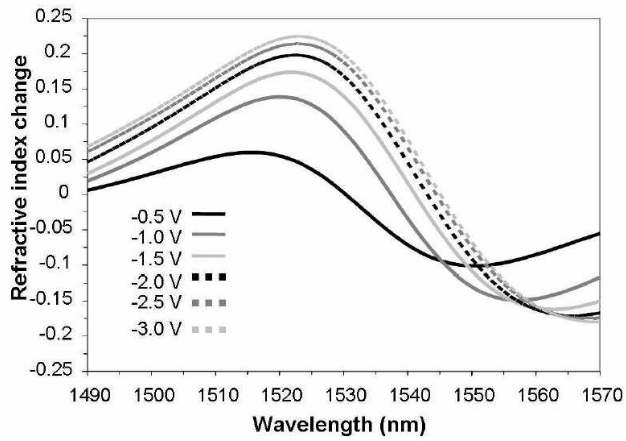


Fig. 5: Refractive index change due to electric field derived from data of Fig. 4. The changes quoted are with reference to the zero-field case.

the frequency detuning while the modulation frequency could remain constant. Figure 3 (right) shows the epitaxial structure of the material used for the laser. The structure was grown by metal-organic vapour phase epitaxy (MOVPE) on a semi-insulating InP substrate. The active region consists of eight 7nm-wide compressively strained (1%) InGaAsP Q1.65 wells, alternating with seven 14 nm-wide tensile strained (0.5%) InGaAsP Q1.3 barriers, sandwiched between two 10 nm-thick InGaAsP Q1.3 waveguide layers. On top of the InGaAs contact layer, a 0.5 µm InP buffer layer and a final 0.1 µm InGaAs buffer layer were grown. They were used to protect the contact cap from damage as shallow ion implantation was used to generate quantum well intermixing (QWI) as in [22]. For this work we implanted 8×10^{14} P ions at 100 keV energy and 200 ^{o}C. With this implantation energy damage was restricted to the buffer layer, thus when it was subsequently removed the surface quality of the contact cap was intact. The wafer was masked with 600 nm of PECVD SiO_2 during implantation in order to protect the gain sections. After implantation the wafer was rapidly thermally processed at 650 ^{o}C for 90 seconds which created a 35 nm blue-shift of the

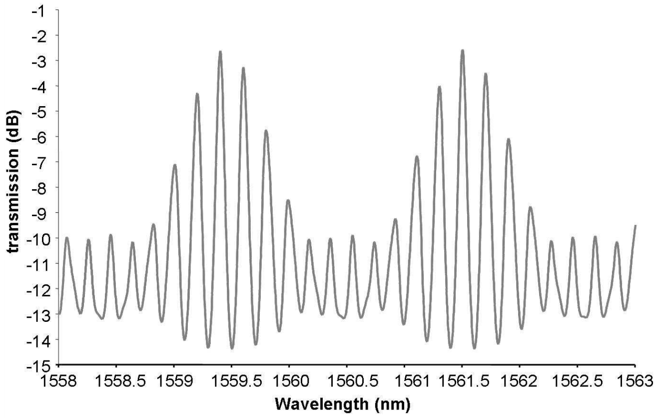


Fig.6: Transmission of the multiple Fabry-Perot cavity

bandgap in the phase and modulator sections. Part of the wafer was then processed into PIN devices, and photocurrent spectra were measured to extract the spectral dependence of the material absorption as a function of reverse bias, as shown in Figure 4. This measurement was used to calculate the effect of QCSE on refractive index by using the Kramers-Kronig relation (Figure 5). This showed that the refractive index for the wells changes by 0.17 with 2 V reverse Bias at a wavelength of 1560 nm (Figure 5). Such an index change in the 170 µm long modulation section corresponds to a phase change sufficient to create the desired FM laser effect at :

$$\Delta\Phi = \frac{2\cdot\pi\cdot\Gamma_{MQW}\cdot\Delta n\cdot L_m}{\lambda} = 10 \ \ \text{rad} \qquad (4),$$

where Δn is the refractive index change of the MQW, Γ_{MQW} is the confinement factor of the guided optical mode within the wells, L_m is the length of the modulation section and λ is the operating wavelength.

The fabricated laser was a ridge waveguide design with oxide-bridged contacts in order to reduce the capacitance of the modulation section (picture in Figure 3.). The different sections were separated by an isolation trench through the highly doped top layers. The oxide-bridged contact for the modulation section allowed a 380 fF measured capacitance and a 20 Ω series resistance resulting in a maximum -3dB modulation bandwidth of 21 GHz. As both phase section and modulation section were intermixed, the laser threshold remained relatively low at 80 mA for a 1.88mm long device. The laser was operated at 200 mA bias current giving a total output of 2 mW (1 mW coupled into a single mode fibre).

The isolation trenches induce a small reflection (~4%) of the propagating mode creating sub-cavity effects. If one considers a trench through the top 1.6 µm of the structure and a two section device, a simulation of the coupled Fabry-Perot cavities created will lead to the calculated transmission function shown in figure 6. As one can see the transmissions spectrum shows regular dips (spaced by 2.1 nm corresponding to a 170 µm sub-cavity) which will strongly affect the output spectrum of the laser. It will offer the advantage of limiting the number of modes operating in the cavity, thus the laser could potentially have single mode free running operation. However

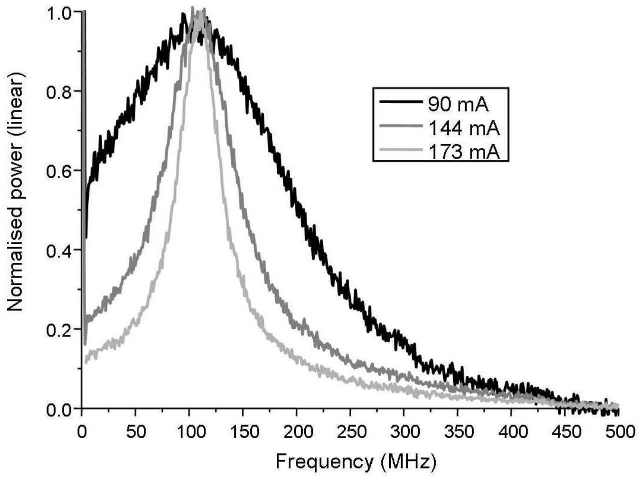


Fig. 7: Free running laser linewidth for current settings from 90 mA (just above threshold) to 173 mA (just below multimode operation)

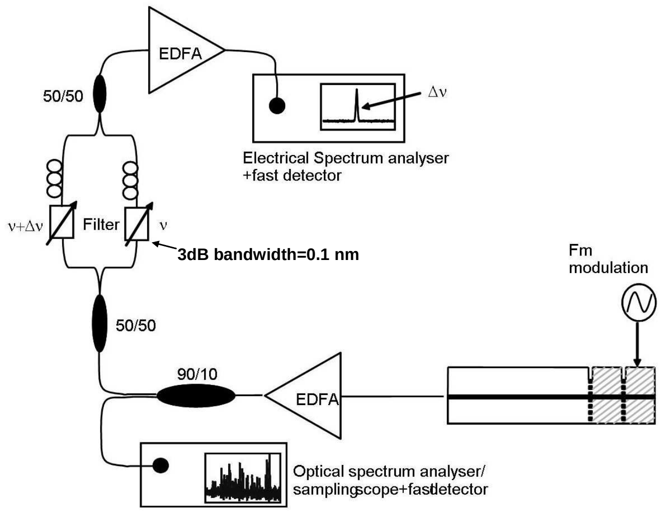


Fig. 8: Experimental system

it will also limit the number of comb lines generated as they will be confined to the spectral zones of higher transmission.

IV. Experiments and Results

Note that for all experimental measurements, the laser output was collected using a lensed fibre with anti-reflection coating which was spliced to an optical isolator in order to eliminate the unwanted effects on laser operation due to external optical feedback.

A. Free running laser

In order to optimize the comb generator operation prior to applying modulation the laser gain current was adjusted to give optimum free-running operation, where the linewidth is at its minimum and the laser operates in a single mode regime. In order to measure the linewidth of the laser mode a self-heterodyne system was used [23]. The delay was 5 km offering a measurement resolution of 40 kHz, which should be sufficient as a typical semiconductor laser will have a linewidth of the order of a few MHz. The linewidth was measured as a function of the gain section current as shown in Figure 7. At low bias current, the laser shows the expected linewidth decrease with increased current. However at a certain bias current (174mA) the linewidth increases sharply to 200 MHz. This was found to be the bias current where the laser starts to operate in a multimode regime. The operation point was therefore chosen to be just below this current. At this bias the laser had an output power of 1.2 mW (0.6 mW coupled into a single mode fibre, operating temperature of 20 ^{o}C) with a linewidth of 25 MHz. Note that the measured width on the RF spectrum analyser is twice the actual linewidth of the laser [23].

B. Modulated laser

Figure 8 shows the different systems used to characterize the FM laser. The output spectrum of the laser was assessed with an optical spectrum analyzer. Finer spectral studies were also done with the same self heterodyne system used previously on the free-running laser in order to assess whether each comb line was retaining the spectral purity of the free-running laser. The laser output power stability was also studied using a fast photodetector (50 GHz bandwidth) and a sampling oscilloscope which was triggered using a reference output from the frequency generator. This allowed residual intensity modulation on the laser output to be studied. As can be seen from Figure 4, the absorption of the modulation section will also change with the voltage thus inducing intensity modulation. Monitoring intensity modulation also enables the transition to mode-locked operation to be observed [21] when the modulation frequency is exactly equal to the axial mode spacing. The stability of the line spacing and its relation to the modulation source frequency were assessed by heterodyning two adjacent lines and sending the resulting signal to the fast photodetector which was connected to a spectrum analyser. Note that the filters were placed at the output of the erbium doped fibre amplifiers (EDFA) to reduce the amplified spontaneous emission (ASE) level in the resulting spectrum. The phase noise as a function of the frequency offset was then extracted and compared to the modulation source phase noise.

Figure 9 shows the output spectrum of the laser with and without 24.4 GHz modulation. The modulation amplitude was chosen to be 2V peak to peak signal with 2V negative bias, where the output spectrum was showing the highest number of comb lines created. With no modulation, lasing was on a single longitudinal mode. With modulation at frequencies much lower than the axial frequency (>1GHz detuning using the frequency source) the laser spectrum only showed the peak and a pair of side lines. With modulation closer to the axial frequency, the spectrum shows a number of lines appearing across the spectrum. When the phase was changed in order to detune the laser axial frequency further from the modulation frequency the number of lines diminished and were closer to the original peak frequency as expected for a FM laser. Note that the spectrum is not symmetric as for the ideal example given previously. This is mainly due to the strong absorption on the short wavelength side of the spectrum, as for this laser

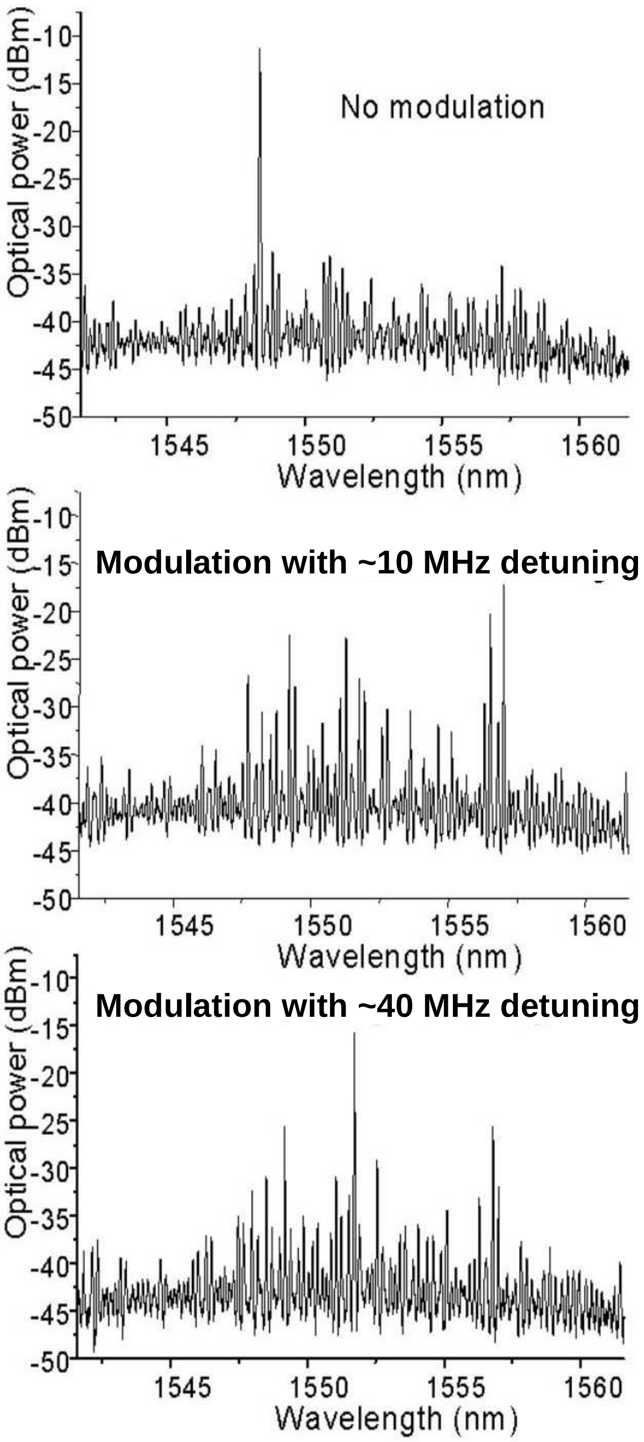


Figure 9: Spectrums with and without modulation

the free running peak wavelength was in the short wavelength side of the gain spectrum. Other lasers operating with a single free running peak in the centre of the gain spectrum operated with a more symmetric comb spectrum, though the number of lines was smaller. This absorption is unavoidable as the intermixing was chosen to be the best balance between low absorption and strong index modulation. This therefore limits the total span of the comb as it reduces the gain bandwidth.

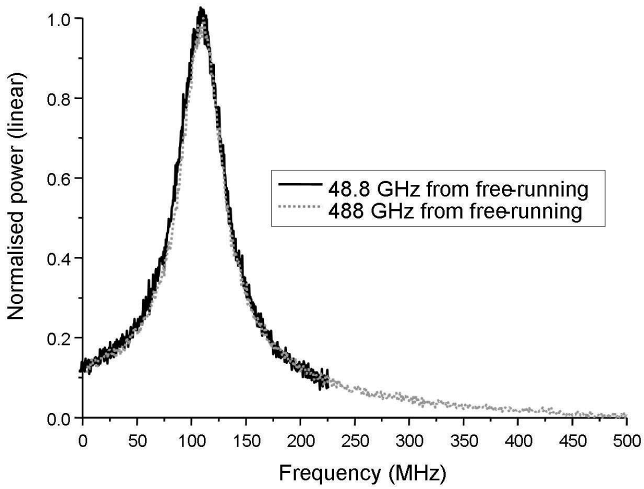


Figure 10: comb lines linewidth measurement

Furthermore, we believe that the trenches used to isolate the different sections, which create a system of coupled Fabry-Perot sub-cavities, are responsible for the lack of lines created at certain points of the spectrum (Figure 9). The simulation result, shown in Figure 6 (for a simpler two sections cavity), indicates that such a cavity design induces higher losses in the cavity at frequency spacing determined by the length of the modulation section. Though the real cavity was not simulated, it is reasonable to assume that a similar effect of zones of higher losses should occur while the periodicity should not be as obvious.

To assess the quality of the created comb lines their linewidth was measured with the self heterodyne system described previously, each line being extracted using a 0.1 nm -3 dB bandwidth filter (13 GHz). Figure 10 shows the linewidth of different comb lines at a given offset from the original free-running laser frequency. As expected, the comb line linewidth remains the same as the linewidth of the free running laser for all comb lines. The linewidth was at its optimum for this laser; i.e. 25 MHz.

As a laser operating in FM regime should show no intensity modulation, to confirm that the device was operating as an FM laser the stability of its output power was measured with a fast photodetector both on a spectrum analyzer and on a sampling oscilloscope. Figure 11 shows the result obtained with the sampling oscilloscope at different points of operation. As one can see at most operation points the output had almost no intensity modulation. However up to 20% intensity modulation appears when the modulation frequency is close to the axial frequency. This was expected as the QCSE only slightly changes the absorption of the modulation section. The spectrum analyzer did also show a weak peak at 24.4 GHz when the modulation frequency was close to the cavity axial frequency, in agreement with the previous measurement. In theory the laser should transition to FM-mode-locked operation when the modulation frequency is exactly equal to the cavity axial frequency. When measured at this frequency the laser showed the same behaviour as with a small detuning

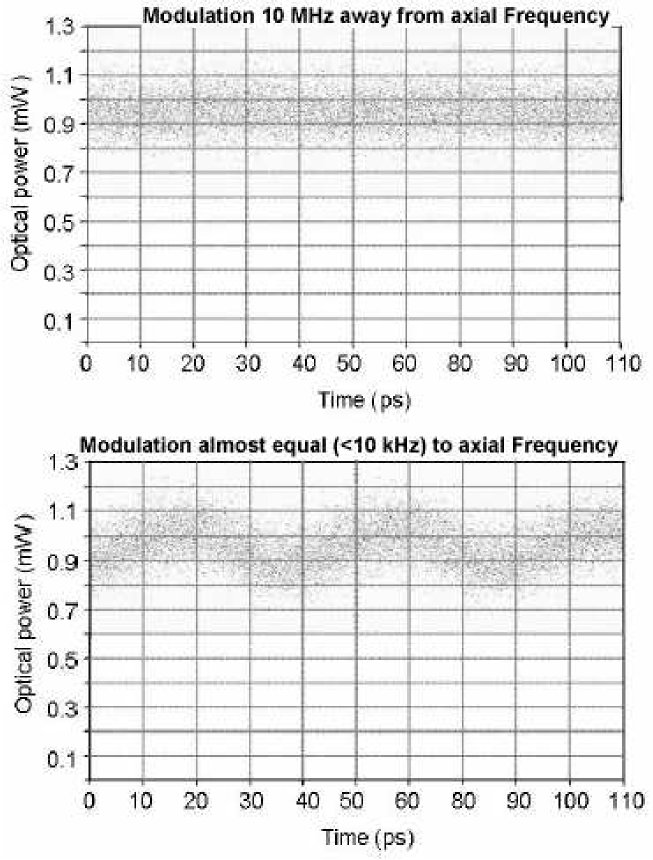


Figure 11: Amplitude modulation measurement at different modulation points

(around 10 kHz), but no mode-locked regime was observed. It is likely that in this device the intra-cavity reflections combined with strong cavity dispersion prevented operation in the mode-locked regime.

This experiment was repeated with individual filtered comb lines in order to assess their intensity stability, and no differences were seen in the measurements compared to the measured intensity modulation of the full output of the laser.

In order to confirm FM operation, the comb line spacing should be measured and its relation to the modulation frequency demonstrated. For this we used the heterodyne system described previously with 0.1 nm (13 GHz) bandwidth filters on each branch of the system. This also offers the advantage of assessing the relative frequency stability of the line spacing.

Figure 12 shows the heterodyne result for one given pair of lines. For this measurement the spectrum analyzer span was 100 kHz and the resolution bandwidth was 1 kHz. The line was at the exact frequency of the modulation source and had the same spectral purity, as expected. Thus, as the comb lines were spaced by the modulation frequency, we could definitely conclude the device was operating as an FM laser. Phase noise measurements were also made on the heterodyne signal to compare it with the modulation source (Figure 13). The phase noise spectral density was obtained [estimated] from the RF power spectrum adjacent to the heterodyne signal (or the

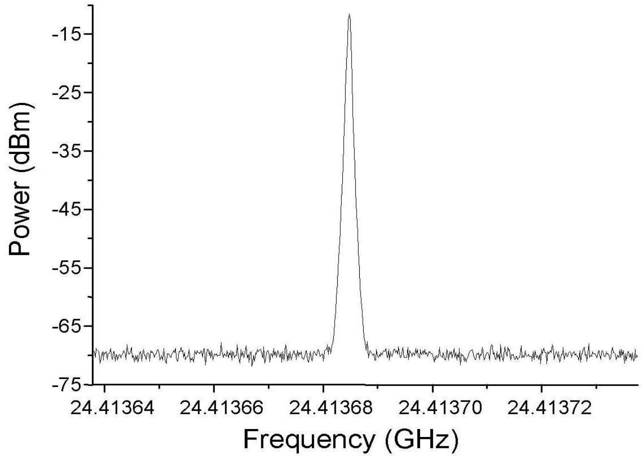


Figure 12: Electrical spectrum of the heterodyne signal created from two adjacent lines of the comb generator.

modulation source signal) by normalising to the peak power in the signal, on the assumption that the phase noise dominates over amplitude noise [24]. The noise floor of the spectrum analyser was around -125 dBm/Hz [check powers] or less for all frequency offsets, while the peak signal powers were around 10 dBm for the modulation source and -10dBm for the heterodyne signal, giving noise floors for the phase noise measurements of around -135 dBc/Hz and -115 dBc/Hz, respectively. As can be seen, up to a frequency offset of about 2 MHz the phase noise is the same for the source and the heterodyne signal, above this frequency offset the noise floor of the spectrum analyzer is reached and no comparison can be made. However this shows that phase noise of -82 dBc/Hz at 1 kHz offset and -108 dBc/Hz at 1 MHz offset can be achieved.

An important issue for the use of this laser as a frequency reference is its absolute frequency stability. Typically a semiconductor laser will show an absolute frequency drift due to the current source instability and thermal drift. The FM laser free running peak wavelength drift was measured over

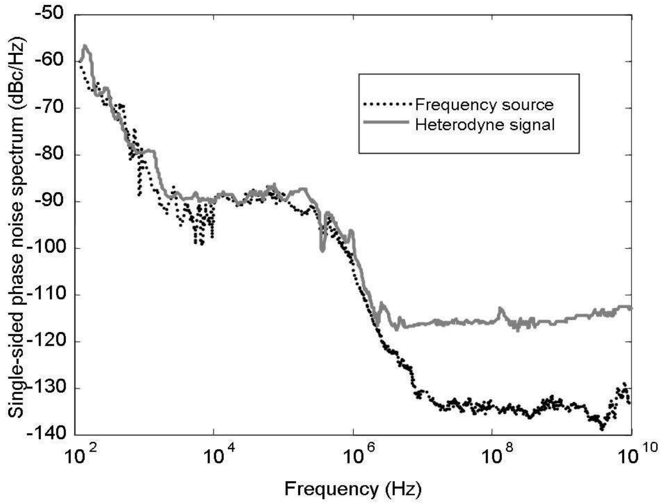


Figure 13: Phase noise measurement of the heterodyne signal from two adjacent comb lines

several hours by heterodyning the laser output with the output of a stabilised DFB laser (on a molecular resonance -acetylene- absolute frequency stability <100 kHz) and observing it on an RF spectrum analyser. It was found to be about 200 MHz with an approximately linear drift for the duration of the measurement. This indicates that the drift is mainly due to the control electronics. Note that this corresponds to a change of the axial frequency of about 100kHz. This is small enough to not affect the FM operation of the laser and confirm the fact that we did not see any change in the comb spectrum over a similarly long operation of the FM laser. In order to obtain a higher absolute frequency stability the laser will need to be locked on an atomic or molecular resonance [25].

V. Conclusion

We have shown the use of a combination of different fabrication techniques in the quaternary/quaternary InGaAsP/InP material to realise a monolithic FM laser comb generator. First the bandgap of part of the wafer was blue shifted using QWI by shallow ion implant and rapid thermal processing (RTP). The 35 nm bandgap shift obtained allowed low signal absorption in the phase and modulation sections of the device. Secondly the fabrication of the device was made using oxide-bridge techniques to reduce the capacitance of the modulation section to 380 fF. This allowed for an efficient reverse bias modulation using QCSE at 24.4 GHz, which was close to the 3 dB bandwidth of the modulation section (21 GHz). The optical frequency comb-generator could potentially offer 24.4 GHz spaced lines over a spectral width of 15 nm (~2THz). However the complexity of the cavity, dispersion and the losses induced by the material were limiting the number of lines created of the potential span. The created laser lines were exactly spaced by the modulation frequency and the residual intensity modulation was less than 20 %. Each line had the same linewidth of 25 MHz as the non modulated laser. When heterodyned, two adjacent lines gave a high purity (-82 dBc/Hz st 1 kHz offset) frequency with phase noise limited by the frequency source. Another limitation for the source is that its absolute frequency stability is limited. A 200 MHz drift measured over a period of several hours was mainly due to the control electronics. We believe that this could be solved by locking the laser on an atomic or molecular resonance. We have isolated two main issues to tackle first in order to improve the performances of the monolithic comb generator. They are the multiple cavity structure and the span of the comb. For the first one we plan to use ion implantation as the section electrical isolation mechanism [26] in order to reduce the level of residual reflection. For the second issue the use of distributed bandgap material will be investigated in order to increase the gain bandwidth [27] of the laser as well as, potentially, the modulation depth [28]. In that case we believe that such monolithic comb generators could provide a compact alternative to fibre loop techniques with larger comb line output powers than passive phase modulator techniques.

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He is a named inventor on 8 US granted patents and over 50 publications in Journals and international conference proceedings. He is also a member of the IEEE.

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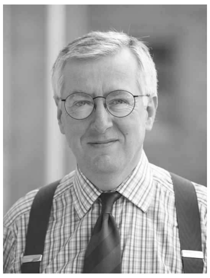
He is a named inventor on one US patent (granted) and is a co-author on over 20 publications in journals and international conference proceedings.

Simon Cole has fifteen years experience in semiconductor materials research. A graduate in Materials Science from Imperial College, London, he gained his PhD from Southampton University, and after two years post-doctoral research at Stanford University and Birmingham University, he joined the MOVPE growth group at BT Research Laboratories in 1984, where he played a key role in the development of overgrowth technologies and was part of the team which won the Queen's Award for Technological Achievement in 1993 for successful transfer of MOVPE-grown device technologies to production. After a number of years as a project manager in software development at BT Laboratories, he joined Corning Research Centre to develop MOVPE overgrowth and butt coupling technologies in support of device programmes. His recent research interests include selective area growth mechanisms around mesa structures and in-situ etching and regrowth. He has authored or co-authored over twenty scientific papers or book articles, a number of patents, and presented work at several international conferences (one invited).

Ron Moore joined BT in 1987 in the MOVPE growth area, was promoted to Technical Officer in 1990 and was a member of the team that won a Queens award for Technological Achievement in 1993. Transferred to Corning in February 2000, with the formation of the Corning Research Centre and was promoted to Scientist grade in 2001.

He joined CIP at it's inception in 2003 and is currently a semiconductor process engineer with responsibility for the Centre's multi wafer growth kit.

Professor Russell Gwilliam is the Director of Technology for the University of Surrey Ion Beam Centre. For the last 20 years he has developed advanced processes and equipment for both III-V and silicon devices and is an active consultant with several international companies. Much of his recent work has been in the area of ion beam synthesis of novel materials, including silicides in both single crystal and amorphous silicon. He is a co-inventor of the silicon light emission technology on which he founded Si-Light Technologies Ltd. He has published more than 250 papers and is a regular invited speaker at international conferences. He is a Member of both the IEE and IoP and sits on several international conference scientific committee's.



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