Conclusion: We have shown that MBE is a viable technique to grow GaN and InGaN layer sequences for LED applications. We demonstrated blue and green photoluminescence as well as bright electroluminescence from GaN/InGaN heterostructures, which to the best of our knowledge, is the first time this has been achieved with MBE grown material.

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Continuously tunable optoelectronic millimetre-wave transmitter using monolithic mode-locked semiconductor laser

D.T.K. Tong and M.C. Wu

Indexing terms: Laser mode locking, Semiconductor junction lasers

The authors demonstrate a continuously tunable optoelectronic transmitter which uses a monolithic mode-locked semiconductor laser. Millimetre-wave subcarrier frequencies up to 300GHz can be generated by photomixing a microwave subcarrier frequency with the selected harmonics of the mode-locked frequency, using an electro-optic modulator. A subcarrier frequency which can be tuned continuously from DC to 43GHz is achieved experimentally.

Introduction: The intrinsic advantages of optical fibre allow efficient transportation of microwave and millimetre-wave (MMW) subcarriers for applications such as remote antenna implementation, fibre-based cellular telephone networks, indoor wireless communication networks, cable television distribution and phased array antennas. In addition to the direct modulation of high-speed semiconductor lasers and the use of the travelling-wave optical modulator, several optical modulation techniques have been reported [1–3]. Mode-locking and resonant modulation of a semiconductor laser results in an enhanced transmission window at the harmonics of the cavity round-trip frequency and is suitable for narrowband systems with a fixed subcarrier frequency in the MMW range [1, 2]. Alternatively, external modulation of an external cavity mode-locked (ML) laser diode [3] can generate a tunable subcarrier frequency ≤ 100GHz. However, MMW subcarrier transmission using an external cavity ML laser source is disadvantaged by low detected power at high harmonic frequencies, due to low repetition frequency and broad pulsewidth. To extend the frequency beyond 100GHz, monolithic ML semiconductor lasers [4] with high repetition frequency and sub-picosecond pulsewidth are required. Optical filtering [5] in conjunction with an optical amplifier can be used to increase the power at the desired harmonics owing to large mode-spacing. In this Letter, we propose and experimentally demonstrate a continuously tunable optoelectronic MMW transmitter using a monolithic colliding-pulse mode-locked (CPM) semiconductor laser. We show that a microwave subcarrier frequency can be upconverted to the MMW range by photomixing with a selected harmonic of the ML frequency ω_{ML} from a monolithic ML semiconductor laser, using an electro-optic modulator (EOM). Because of the monolithic cavity length, the harmonics of the ML frequency lie in the MMW range and this technique is capable of allowing continuously tunable subcarrier frequencies ≤ 300GHz.

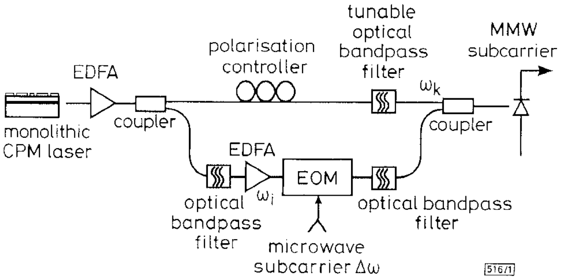

Fig. 1 *Schematic diagram of continuously tunable optoelectronic MMW transmitter*

Experiment: Fig. 1 illustrates the experimental setup for the continuously tunable MMW optoelectronic transmitter demonstration. A 38GHz hybrid monolithic CPM InGaAs/InGaAsP quantum well laser [4] provides an array of phase-locked optical frequencies, $\{\omega_1, \omega_2, ..., \omega_k\}$, which collectively form an ML supermode. The ML supermode is first amplified using an erbium-doped fibre amplifier (EDFA) before being split into two branches by a 3dB coupler. A desirable harmonic of the ML frequency ω_{ML} can be selected by optically filtering two appropriate optical modes (e.g. ω_i and ω_k) from the ML supermode for the upconversion of the microwave subcarrier frequency. The centre mode of the mode-locked supermode ω_i is extracted in the lower branch using a fibre Fabry-Perot (FP) filter with 10GHz bandwidth. A second EDFA is used to further amplify ω_i before being fed to the EOM. The EOM used in this experiment is an $LiNbO_3$ Mach-Zehnder intensity modulator with 5GHz bandwidth. A microwave subcarrier frequency $\Delta\omega$ is modulated on ω_i using the EOM. Two 40GHz bandwidth FP filters are used to remove the amplified spontaneous emission (ASE) noise introduced by the EDFAs. The FP filter in the upper branch also functions as an optical bandpass filter to select the other ML mode ω_k for optical heterodyning. The polarisation controller ensures proper alignment of the signals' polarisations where they are mixed. The detected signal is down-converted by a microwave harmonic mixer, amplified and then displayed by a microwave spectrum analyser. The photocurrent generated by photomixing ω_k and the modulation sidebands of ω_i is proportional to

$$\begin{aligned} I_p &\propto \left| A_k e^{j\omega_k t} + m A_i e^{j(\omega_i \pm \Delta\omega)t} \right|^2 \\ &\propto A_k^2 + m^2 A_i^2 + 2m A_i A_k \cos(n\omega_{ML} \pm \Delta\omega)t \qquad (1) \end{aligned}$$

where A_i and A_k are the field amplitude coefficients of ω_i and ω_k at the photodetector, respectively; m is the modulation index for ω_i, and n is an integer since both ω_i and ω_k belongs to the ML supermode. The first and the second terms in eqn. 1 are DC components and can be neglected. The third term is the upconverted MMW subcarrier frequency $\omega_{SC} = n \cdot \omega_{ML} \pm \Delta\omega$.

Results and discussion: Fig. 2 shows the upconverted MMW subcarrier frequency against modulation microwave subcarrier frequency. The lines with positive and negative slopes represent the MMW subcarrier frequency equal to multiples of the ML frequency, plus and minus the microwave subcarrier frequency, respectively. As shown in Fig. 2, the maximum required tuning range of the modulating microwave subcarrier frequency $\Delta\omega$ is equal to half the ML frequency. Therefore, by varying $\Delta\omega$ (up to $\omega_{ML}/2$) and by appropriate selection of the optical modes (e.g. ω_i and ω_j), a continuously tunable subcarrier frequency across the entire bandwidth of the mode-locked spectrum is possible. A typical CPM laser has a transform-limited pulse of ~1ps pulsewidth and 0.31 time-bandwidth product. This provides a continuous tuning range of 300GHz. Further reduction of pulsewidth can extend the tuning range. For the 38GHz CPM laser, a commercially available EOM with 19GHz bandwidth can be used. The EOM used in our experimental setup has a bandwidth of only 5GHz, and for the purpose of demonstrating the continuous tuning of the MMW subcarrier frequency, the overdrive technique as described in [6] is used. The EOM is low-biased to generate second or fourth harmonics of the modulating microwave frequency, while keeping lower harmonics null. Owing to the limitation on the bandwidth of the photodetector (HP 83440D, BW = 34GHz), the microwave amplifier and the harmonic mixer used in our experiment, the MMW subcarriers with frequencies up to 43GHz are measured. The measured frequencies agree well with the theoretical prediction.

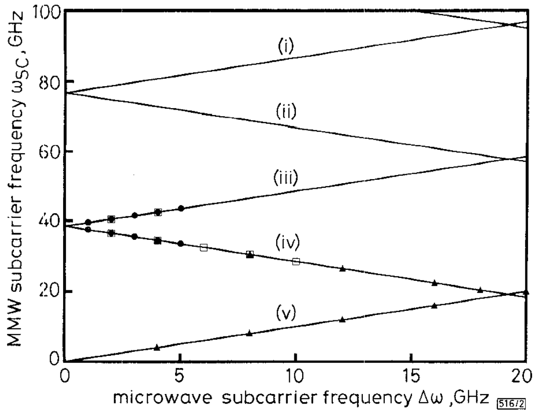

Fig. 2 *Generated MMW subcarrier frequency ω_{sc} against modulating microwave subcarrier frequency $\Delta\omega$*

Positive- and negative-slope lines indicate generated signal frequencies equal to multiples of mode-locked frequency plus and minus the modulating frequency, respectively. The graph also shows the measured signal frequencies generated by the harmonics of the EOM modulating frequency:
● fundamental
□ second
△ fourth
(i) $2\omega_{ML} + \Delta\omega$, (ii) $2\omega_{ML} - \Delta\omega$, (iii) $\omega_{ML} + \Delta\omega$, (iv) $\omega_{ML} - \Delta\omega$, (v) $\Delta\omega$

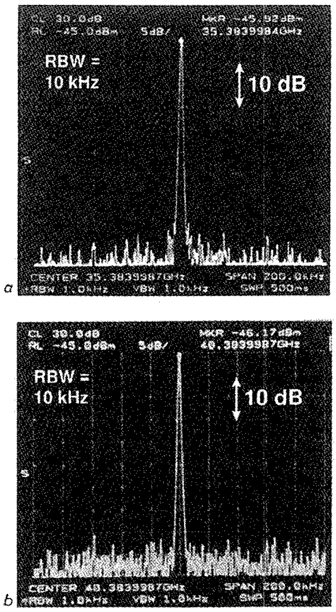

Fig. 3 *MMW subcarrier at various frequencies*

Subcarrier frequencies:
a 35GHz
b 40GHz
The CNR is 75dB (1Hz)

Fig. 3 shows the RF spectra of the generated MMW subcarriers at various frequencies. The measured CNR for the MMW subcarrier, generated by the fundamental, the second and the fourth harmonic of the modulating frequency, are 75, 73 and 70dB (1Hz), respectively. Eqn. 1 indicates that, since the current at the MMW subcarrier frequency is proportional to mA_iA_k, the power of the generated MMW subcarrier can be maintained by increasing either A_i or A_k, thus avoiding potential signal distortion when m is large.

Conclusion: A continuously tunable optoelectronic transmitter is demonstrated for broadband, multichannel millimetre-wave subcarrier transmission. This scheme is capable of transmitting a subcarrier frequency ≤ 300GHz with two relatively low frequencies: (38GHz) for mode-locking the laser diode, and (≤19GHz) for continuously tuning the millimetre-wave subcarrier.

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Integrated electrostatic micro-switch for optical fibre networks driven by low voltage

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Indexing terms: Electrostatic devices, Optical switches

An improved microswitch for optical networks is presented. Fully integrated on silicon substrate by means of integrated optics technology, it is well suited for mass production. It is characterised by low insertion losses, very low polarisation and wavelength dependence and low driving power.