Conclusion: We have shown that MBE is a viable technique to grow GaN and InGaN layers suitable for LED applications. We demonstrated that blue and green photoluminescence 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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References


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

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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 300 GHz can be generated by photonically mixing 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 43 GHz is achieved experimentally.

Introduction: The intrinsic advantages of optical fibre allow efficient transportation of 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 ≤ 100 GHz. 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 bandwidth. To extend the frequency beyond 100 GHz, 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 ωML from a monolithic ML semiconductor laser, using an electro-optic modulator (EOM) [6]. 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 ≤ 300 GHz.

Experiment: Fig. 1 illustrates the experimental setup for the continuously tunable MMW optoelectronic transmitter demonstration. A 38 GHz hybrid monolithic CPM InGaAs/InGaAsP quantum well laser [4] provides an array of phase-locked optical frequencies ω0, ω0, ω0, ω0, ..., 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 ωnML can be selected by optically filtering two appropriate optical modes (e.g. ω0 and ω0) from the ML supermode for the upconversion of the microwave subcarrier frequency. The centre mode of the mode-locked supermode ω0 is extracted in the lower branch using a fibre Fabry-Perot (FP) filter with 10 GHz bandwidth. A second EDFA is used to further amplify ω0 before being fed to the EOM. The EOM used in this experiment is an LiNBO3 Mach-Zehnder intensity modulator with 5 GHz bandwidth. A microwave subcarrier frequency ωω can be modulated on ω0 using the EOM. Two 40 GHz bandwidth FP filters are used to remove the amplified spontaneous emission (ASE) noise introduced by the EDFA. The FP filter in the upper branch also functions as an optical bandpass filter to select the other ML mode ω0 for optical heterodyning. The polarisation controller ensures proper alignment of the signal's 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 ω0 and the modulation sidebands of ω0 is proportional to

\[
I_p \propto A_p e^{i\omega t} + m A_p e^{i\omega (\sin \theta + \Delta \omega)t}
\]

where \(A_p\) and \(A_p\) are the field amplitude coefficients of \(\omega_0\) and \(\omega_0\) at the photodetector, respectively; \(m\) is the modulation index for \(\omega_0\) and \(n\) is an integer since both \(\omega_0\) and \(\omega_0\) belong 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 \(\omega_{\text{MMW}} = n \omega_0 + \Delta \omega\).

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 fre-
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. 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 \( mA_0 \), the power of the generated MMW subcarrier can be maintained by increasing either \( A_1 \) or \( A_2 \), 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 \( \leq 300\)GHz 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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