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## Suppression of second harmonic distortion in directly modulated distributed feedback lasers by external light injection

X.J. Meng, T. Chau, D.T.K. Tong and M.C. Wu

The suppression of second harmonic distortion in directly modulated semiconductor distributed feedback lasers by optical injection locking has been experimentally demonstrated. Reduction of second harmonic distortion by more than 10dB has been observed over a wide range of bias currents and modulation frequencies.

**Introduction:** Microwave subcarrier multiplexed (SCM) fibre optic systems have attracted a great deal of attention for applications in broadband local access networks and fibre-radio systems [2, 3]. Both direct modulation of semiconductor lasers and external modulation have been used in SCM systems. The direct modulation approach is simpler and has lower cost; however, its link performance is usually limited by nonlinear distortion in the semiconductor lasers. The low-frequency nonlinearity is mainly caused by the nonlinear light/current characteristics. For SCM systems that operate in the L- and S-bands (1-4GHz), the nonlinear interaction between electrons and photons in the laser cavity is the main cause of the nonlinear distortion [4, 5]. The nonlinear distortion is compounded by the resonance due to relaxation oscillations. Recently, Yabre *et al.* showed theoretically that optical injection locking can substantially reduce laser nonlinearities [6]. In this Letter, we report the first experimental observation of the reduction of second harmonic distortion (SHD) in directly modulated semiconductor lasers by optical injection locking. Suppression of the SHD by more than 11dB has been achieved over wide frequency and bias ranges.

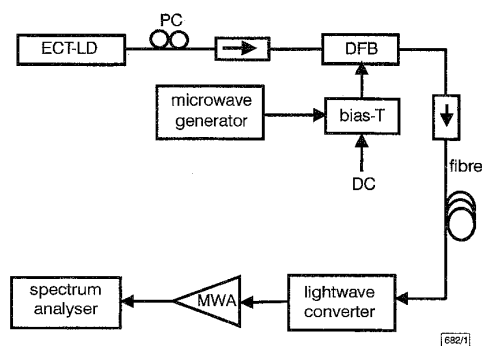


Fig. 1 Experimental setup

PC: polarisation control; ECT-LD: external cavity tunable laser diode; DFB-LD: DFB laser diode

**Experiments:** The experimental setup is shown in Fig. 1. The master laser used in this experiment is a commercial external-cavity tunable laser diode (ECT-LD) at 1.55 $\mu$ m with a tuning step of

1GHz and a linewidth of < 200kHz. CW light from the ECT-LD is injected into the slave laser through a polarisation controller and an optical isolator. The slave laser is a 1.55 $\mu$ m single-longitudinal mode distributed feedback (DFB) laser diode with a threshold current  $I_{th}$  of 23mA. The DFB laser is directly modulated by a multigigahertz microwave signal through a bias-T. At the receiver side, the optical signal is detected and amplified by a 15GHz lightwave converter (HP 11982A) with a responsivity of 300V/W. It is followed by another microwave amplifier with 27dB gain. The output is connected to a microwave spectrum analyser (HP 8592A). The second harmonic distortion (SHD) is defined as the power ratio of the second harmonic wave to the fundamental wave. The injection locking condition is determined by monitoring the linewidth of the slave laser, which is measured by the modified delayed self-heterodyne (MDSHM) scheme suggested by Esman *et al.* [7].

Fig. 2a shows the measured microwave spectrum of the free-running DFB laser. The laser is biased at 40mA ( $\approx 1.75I_{th}$ ) and modulated by a 3.4GHz microwave signal. The microwave power is kept at -2dBm. The relaxation oscillation frequency of the laser is 4.1GHz under this bias condition. The SHD of the free-running laser is -18.6dBc. Fig. 2b shows the corresponding spectrum of the laser under injection locking. The SHD has been dramatically reduced to -38.9dBc. The injection ratio and detuning frequency are -8dB and -15GHz, respectively, which are located in the middle of the stable locking range. Under this injection condition, the measured relaxation oscillation frequency is increased to 13.6GHz, which is nearly three times that of the free-running laser [8].

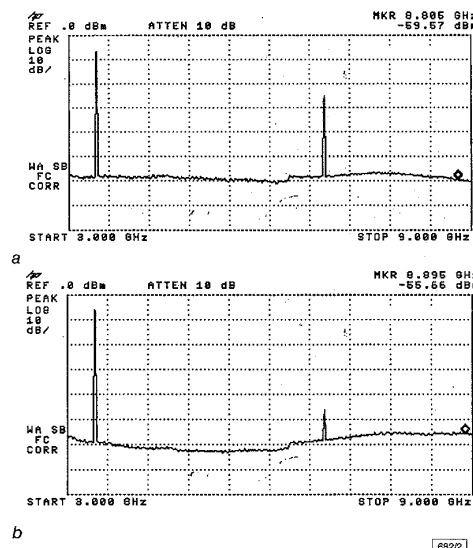


Fig. 2 Microwave spectrum of free-running and injection-locked DFB laser under direct modulation at 3.4GHz

Second-harmonic peak at 6.8GHz is greatly suppressed in injection-locked laser  
a Free-running  
b Injection locked

The reduction in SHD can be intuitively explained as follows. The nonlinear distortion becomes more severe as the modulating frequency approaches the relaxation oscillation frequency due to the nonlinear coupling between electrons and photons. The theoretical calculations using the small signal analysis of rate equations have suggested that, by moving the relaxation oscillation to a much higher frequency, the nonlinear distortion can be greatly reduced [5]. Optical injection locking has been shown both theoretically [6] and experimentally [8] to be very effective in increasing the relaxation oscillation frequency of semiconductor lasers.

Fig. 3 shows the measured SHD with and without external optical injection as a function of the bias current for three different modulation frequencies. The injection parameters are the same as those used in Fig. 2b. Without external optical injection, the SHD is very high. For example, the SHD is greater than -25dBc at 3GHz. With injection locking, the SHD is suppressed by more than 10 dB over the entire bias range from 30 to 50mA and mod-

ulating frequency from 1 to 3 GHz. Another interesting feature is that, unlike the free-running laser, the SHD of the injection-locked laser is less dependent on the modulating frequency. The SHD at 2 and 3 GHz is lower than that at 1 GHz.

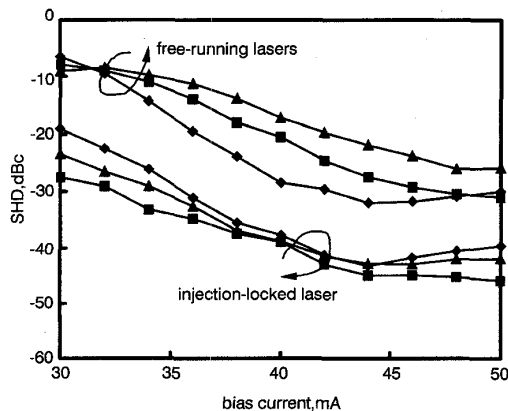


Fig. 3 Second harmonic distortion against bias current for free-running laser and injection-locked laser for three modulation frequencies

● 1 GHz  
■ 2 GHz  
▲ 3 GHz

**Conclusion:** In conclusion, we have investigated the second harmonic distortion of a directly modulated DFB laser with and without optical injection locking. The experimental results show that the second harmonic distortion of the DFB laser has been suppressed by more than 10dB over a wide range of modulating frequencies and bias currents.

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## Realisation of magnetic conducting surface using novel photonic bandgap structure

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The realisation of a magnetic conducting surface using a novel two-dimensional uniplanar photonic bandgap structure is described. This novel idea is verified by measured results and the results obtained using the finite-difference time-domain method.

**Introduction:** The case of an electric dipole above a perfectly electric conducting ground plane (PEC) represents a canonical electromagnetic problem and has been analysed extensively [1]. The results can be used for constructing antennas such as a monopole antenna with a PEC ground plane. The dual of this canonical problem is a magnetic dipole radiating above a perfectly magnetic conductor (PMC). In contrast to the realisation of a PEC, which is not difficult in practical situations, the realisation of a PMC remains a difficult task. The difficulty stems from the fact that no suitable material has been found which can be used as a PMC.

In this Letter, a novel 2D uniplanar photonic bandgap (PBG) structure is employed to realise the magnetic conducting surface. This novel PBG structure has the advantage of easier fabrication than other types of PBG structure which always require vias [2]. The characteristics of the constructed PBG magnetic surface are measured and the FD-TD (finite-difference time-domain) method [3] is employed to analyse this novel magnetic surface. Good agreement found between the measured and numerical results verifies this novel concept of realising a magnetic surface.

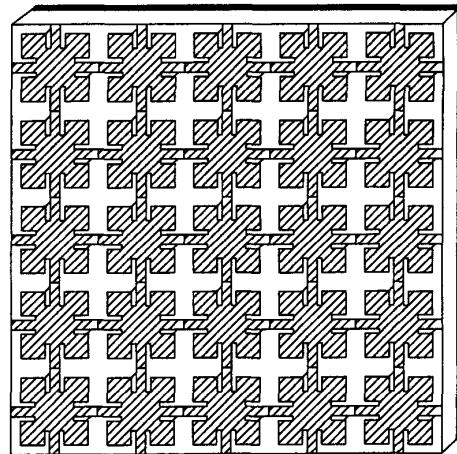


Fig. 1 2D photonic bandgap structure used for realising magnetic surface

**Theory:** The basic difference in the electrical properties between an infinitely large PEC and PMC can be characterised by the reflection coefficient for a uniform incident plane wave. The magnitudes of the reflection coefficient for both cases are the same and equal to one, while the phase differs by 180°. Another view of the difference between a PEC and a PMC can be made by looking at the surface impedance of a PEC and a PMC. A PMC appears as an open circuit seen from the incoming plane wave, and one way to provide the open circuit condition is to create a periodic pattern. Each element of this periodic pattern provides an equivalent L and C parallel connection which changes the surface impedance. At the frequencies where the periodic loading becomes open, a magnetic surface is created. A newly proposed 2D uniplanar PBG pattern [4], as shown in Fig. 1, is one of the candidates for fulfilling this purpose. This novel PBG pattern has the advantage of being simple and can be easily fabricated using any standard planar process without the need for vias, which are necessary for other types of PBG structure [2, 5].

**Experimental setup:** The experimental setup consists of two X band horn antennas and an HP 8720A network analyser. The two horn antennas, one for transmitting and the other for receiving,