Tapping-mode tuning-fork near-field scanning optical microscopy of low power semiconductor lasers

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Summary

The newly developed inverted tapping-mode tuning-fork near-field scanning optical microscopy (TMTF-NSOM) is used to study the local near-field optical properties of strained AlGaInP/Ga_{0.4}In_{0.6}P low power visible multiquantum-well laser diodes. In contrast to shear-force mode NSOM, TMTF-NSOM provides the function to acquire the evanescent wave intensity ratio $|I(2\omega)|/|I(\omega)|$ image, from which the evanescent wave decay coefficient q can be evaluated for a known tapping amplitude. Moreover, we probe the near-field stimulated emission spectrum, which gives the free-space laser light wavelength λ_o and the index of refraction n_r of the laser diode resonant cavity. Once q , λ_o , and n_r are all measured, we can determine the angle of incidence θ_o of the dominant totally internally reflected waves incident on the front mirror facet of the resonator. Determination of such an angle is very important in modelling the stability of the laser diode resonator.

Introduction

Semiconductor lasers have become indispensable commercial components to our everyday life. For example, they are widely used in an increasing number of applications ranging from the light sources for optical information processing systems such as bar-code scanning, high-speed laser printing, and optical read/write recording to the transmitters in optical fibre telecommunications in recent years. Accordingly, characterization and further understanding of the performance and reliability of various semiconductor laser structures turn out to be important tasks. Because of the superior spatial resolution of near-field

scanning optical microscopy (NSOM) and the ease of implementation of local spectroscopy, lately NSOM has played a key role in optical imaging and spectroscopic study in the diagnostics of semiconductor lasers (Hörsch *et al.*, 1996; Lienau *et al.* 1997; Ben-Ami *et al.*, 1998; Kim *et al.*, 2000).

Recently Lu *et al.* (1999) applied both collection and excitation modes of NSOM to study the optical properties of low power strained AlGaInP/Ga_{0.4}In_{0.6}P visible multiquantum-well laser diodes (MQWLDs). The results show that both the near-field optical beam induced current and the near-field electroluminescence can be studied in the same region on a nanometer-sized length scale, which demonstrates the effective advantages of NSOM – that different operation modes of NSOM can serve as complementary local characterization techniques to one another. Furthermore, the defect location and the energy range of defect level can be resolved by the excitation mode of NSOM using pump sources of different wavelengths.

In this paper, the newly developed novel method, tapping-mode tuning-fork near-field scanning optical microscopy (TMTF-NSOM) (Tsai & Lu, 1998), is used to study the local near-field optical properties of low power visible MQWLDs. As has been demonstrated by Tsai *et al.* (1999), TMTF-NSOM has the ability to perform evanescent wave intensity ratio imaging. Thus we can determine the decay coefficient of the evanescent fields due to the totally internally reflected waves incident on the front mirror facet of the laser diode (LD) resonant cavity, on condition that the tapping amplitude of the fibre tip is small and known.

Experimental

The inverted TMTF-NSOM was used to probe the near-field optical signals on the emission edge of the LD by collection mode. A schematic of the experimental set-up is shown in Fig. 1. For imaging acquisition, light coupled to the tapered

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Fig. 1. A schematic diagram of the experimental set-up for measuring the near-field intensity ratio image on the emission facet of a laser diode. An inverted TMTF-NSOM system with two external lock-in amplifiers is used to simultaneously provide images of both the topography and the optical intensity signals of $|I(\omega)|$, $|I(2\omega)|$, or their intensity ratio $|I(2\omega)|/|I(\omega)|$.

fibre tip engaged in the near-field region was detected by a photomultiplier tube, the output signal of which was fed to two external lock-in amplifiers. The lock-in amplifiers acquired signals at the tapping frequency ω and its second harmonic counterpart 2ω , and provided their intensity ratio $|I(2\omega)|/|I(\omega)|$. The distance regulation between the sample surface and the cusp of the fibre probe was realized by another internal lock-in amplifier of a commercial electronic control unit of an atomic force microscope (AFM), which has been described elsewhere (Tsai & Lu, 1998; Tsai *et al.*, 1999). The feedback control of the probe height is a non-optical method and has all the advantages afforded by the tapping-mode AFM scheme, including high spatial resolution, high sensitivity, and excellent stability. Images of the topographic and near-field optical signals are acquired simultaneously. For spectroscopic characterization, the light collected by the tapered fibre probe was delivered to a 0.3-m optical spectrometer fitted with a liquid nitrogen cooled multichannel charge-coupled device (CCD). The spectral resolution of our system is 0.1 nm. The epitaxial structure of the LD is similar to that reported elsewhere (Lu *et al.*, 1999), except that the quantum well thickness is 5 nm and the resonant cavity length L , 400 μm .

Results and discussion

In contrast to shear-force mode NSOM, which can obtain the near-field emission intensity signal, TMTF-NSOM provides the function to acquire the evanescent wave intensity ratio $|I(2\omega)|/|I(\omega)|$ image. The near-field optical intensity I emanating from an LD emission surface can be expressed as $I = I_p + I_o e^{-2qz}$, where I_p represents the constant propagating term, I_o denotes the evanescent wave intensity at the surface of the LD emission edge, z is the probe height above the LD emission surface, and q , the decay coefficient. Given that the index of refraction of the semiconductor laser resonant cavity is 3.0, the total-internal-reflection angle of the resonator/air interface is $19.5^\circ (= \sin^{-1} 1/3)$. The evanescent component is due chiefly to the light waves propagating within the resonator when they strike the front mirror facet at an angle of incidence θ_o beyond the total-internal-reflection angle, which is a condition easily satisfied. The decay coefficient is derived as

$$q = (2\pi/\lambda_o)(n_r^2 \sin^2 \theta_o - 1)^{1/2} \quad (1)$$

where n_r is the index of refraction of the LD resonant cavity

and λ_0 is the free-space light wavelength (van Hulst *et al.* 1992). Based upon the above argument, the actual angle of incidence of the dominant totally internally reflected waves incident on the output coupler can be experimentally determined if λ_0 , n_r and q are all measured. This will be demonstrated below.

Instead of working in the constant height (constant z) mode in conventional near-field microscopes, z is modulated in TMTF-NSOM: $z = z_0 + A \cos \omega t$, in which A and z_0 represent the tapping amplitude of the probe and the closest distance between tip and sample surface, respectively (Tsai *et al.*, 1999). For a small tapping amplitude (i.e. $qA < 1$), the evanescent wave intensity ratio of $|I(2\omega)|$ to $|I(\omega)|$ can be approximated as $|I(2\omega)|/|I(\omega)| \cong [qA + (1/3)q^3A^3]/(2 + q^2A^2)$. Therefore, measurement of $|I(2\omega)|/|I(\omega)|$ will directly give the value of q if the tapping amplitude is known.

Plotted in Fig. 2(a) and (b) are the $5 \mu\text{m} \times 5 \mu\text{m}$ AFM topography and evanescent wave intensity ratio $|I(2\omega)|/|I(\omega)|$ image of the emitted light at the front mirror facet of a strained AlGaInP/GaInP MQWLD operating with injection current just above its threshold. As is shown, the intensity ratio image shows one ellipse-like spot just below the p electrode in the positive-intrinsic-negative junction. Also displayed in the inset is the intensity ratio linecut along the central line perpendicular to the MQW epitaxial layers. Obviously the profile exhibits a plateau structure with a smooth fall-off on the edge. Actually the intensity ratio image displays a rather uniform output distribution over the entire brighter contrast region. The full width at half

maximum (FWHM) of the cross-sectional evanescent wave intensity ratio profile in the direction normal to the epitaxial layers is 762 nm and that in the direction parallel to the epitaxial layers is $3.0 \mu\text{m}$.

The intensity ratio signals give the value of q if the tapping amplitude is known (Tsai *et al.*, 1999). The tapping amplitude is estimated to be 65 nm from an interferometric measurement. Since $|I(2\omega)|/|I(\omega)| = 0.33$, the decay coefficient q is determined to be 0.011 nm^{-1} . The evanescent fields emerge from LD resonator to air with an exponentially decreasing density of energy transferred in the z direction. Obviously the evanescent wave intensity decay length, defined as $d_p = 1/2q$, is calculated to be 45 nm.

Figure 3 shows the near-field stimulated emission spectrum of the LD when the tip is positioned at the centre of the active region. The injection current is the same as that operated in Fig. 2. As can be seen, the emission spectrum exhibits multiple peak structures around their centre wavelength, 654.49 nm, and the free spectral range is $\Delta\lambda_{\text{FSR}} = 0.17 \text{ nm}$. Since the wavelength dependence of n_r is negligible in our case (Adachi *et al.*, 1994), the free spectral range can be given by $\Delta\lambda_{\text{FSR}} = \lambda_0^2/2n_rL$, where λ_0 is chosen to be the centre wavelength in vacuum in our calculation. Therefore, the refractive index of the LD structure is readily calculated as $n_r = 3.15$. Substituting $n_r = 3.15$, $\lambda_0 = 654.49 \text{ nm}$, and the previously determined $q = 0.011 \text{ nm}^{-1}$ into Eq. (1), we can obtain $\theta_0 = 29^\circ$. The result shows that the evanescent waves are due chiefly to the inside-cavity propagating waves incident on the front mirror facet at an angle of 29° . Determination

Fig. 2. $5 \mu\text{m} \times 5 \mu\text{m}$ scanned NSOM images of (a) AFM topography and (b) evanescent wave intensity ratio $|I(2\omega)|/|I(\omega)|$ on the emission facet of a strained AlGaInP/Ga_{0.4}In_{0.6}P low power visible MQWLD operating just above the threshold current. Also shown in the inset is the intensity ratio linecut along the central line perpendicular to the MQW epitaxial layers.

Fig. 3. Near-field stimulated emission spectrum of the LD when the tip is positioned at the centre of the active region. The spectral output exhibits several peak structures around their centre wavelength (654.49 nm) with a constant peak separation of 0.17 nm.

of such an angle is very important in modelling the stability of the laser diode resonator.

Conclusions

As has been pointed out by van Hulst *et al.* (1992), there exists problems in isolating the evanescent field component when lateral-force mode evanescent field optical microscope (or photon scanning tunneling microscope) is applied to probe the evanescent wave generated by total internal reflection at a substrate surface, on which roughness induced field mixing of the radiative waves with the evanescent ones is inevitable. They also suggest that the *z*-modulation technique should be one of the possible solutions. Here we have demonstrated how TMTF-NSOM can be used to measure the evanescent wave decay coefficient of the light emanating from the LD facet if the tapping amplitude of the fibre probe is small and known. Furthermore, the light wavelength and the index of refraction of the resonant cavity are obtained from the near-field stimulated emission spectrum of the LD. In consequence, we can experimentally determine the angle

of incidence of the dominant totally internally reflected beams incident on the front mirror facet of the LD.

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