Analysis of phase-matching conditions for internal second-harmonic generation in InGaAs quantum-well laser diodes

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ABSTRACT

In this paper we present an analysis of the phase-matching conditions for internal second-harmonic generation in InGaAs quantum-well laser diodes in order to enhance the conversion efficiency. We have characterised the role of phase-mismatching in the spectral distribution of the internal second-harmonic generation in the CW operation of these lasers. The emission of pairs of narrow blue-green peaks having perfectly symmetrical spectral positions with respect to the central peak of pure second-harmonic generation at ~ 480 nm is most probably enhanced by a mechanism of reciprocal cancellation of the respective phase-mismatch vectors. This study is important for the assessment of the relationship between the structural parameters of the laser and the conditions which contribute to the stimulation of second-order optical nonlinearities in the laser active region.

Keywords: InGaAs quantum-well laser diodes, spectral characterization, second-harmonic generation

1. INTRODUCTION

The enhancement of the performances of the laser diodes emitting high radiant power in the spectral region around 980 nm, like the efficiency and reliability is of high interest for technological applications such as the optical pumping of Er^{3+}-doped fiber amplifiers and of solid-state lasers, and in medical therapy[1, 2]. At the same time, these devices can be useful light sources for fundamental research in high resolution optical spectroscopy and nonlinear optics.

The internal second-harmonic generation (ISHG) in laser diodes has been studied since the early '60s when it was observed for the first time in GaAs-based lasers[3, 4]. So far, the ISHG has been reported for various other III-V semiconductor laser active region compositions, such as InGaAsP/InP and InGaAs/GaAs[5]. The study of the ISHG in near infrared laser diodes has provided relevant information for the application of the blue-green second-harmonic emission in absorption spectroscopy and for the investigation of the optical power density build-up in the mirror facet layer[5].

The objective of our work was to develop a clear physical picture of the mechanisms governing the generation of the second harmonic signals in the laser waveguide.

This study is important for the assessment of the relationship between the structural parameters of the laser and the conditions which contribute to the stimulation of second-order optical nonlinearities in the laser active region.

2. DISCUSSION OF THE EXPERIMENTAL RESULTS

We studied an InGaAs/GaAs/AlGaAs quantum-well laser diode grown by liquid-phase epitaxy on an exact oriented (100) GaAs substrate[1, 2]. The laser cavity in this sample is 0.96 mm long and the transversal geometry of the gain region is of the ridge-waveguide type with a stripe as wide as 100 μm. The active region is a separate confinement heterostructure with an 80 Å–wide $In_{0.2}Ga_{0.8}As$ quantum well. The laser crystal was fixed on a copper heat sink which also was in tight thermal contact with a Peltier module for the variation of the sample temperature.

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ROMOPTO 2000: Sixth Conference on Optics, Valentin I. Vlad, Editor,
Proceedings of SPIE Vol. 4430 (2001) © 2001 SPIE · 0277-786X/01/$15.00

The experimental work was carried out by recording the spectra of the fundamental emission and of the second-harmonic generation by means of a standard spectroscopic system composed of a 0.15m spectrometer from Acton Research and an R955 Hamamatsu photomultiplier. The recorded spectra were subsequently corrected for the spectral profiles of both the photomultiplier and the diffraction grating. The integration of the spectra allowed us to obtain the quantitative information regarding the relative variation of the radiant power emitted in both the fundamental wave and the second-harmonic signals as a function of both the continuous injection level and the sample temperature. Several identical samples were studied in the same conditions in order for us to be able to confirm the repeatability of the ISHG results.

The typical ISHG spectrum emitted by this laser structure is shown in Fig. 1. The peculiarity of this spectrum is the presence of several pairs of narrow peaks symmetrically distributed on either side of the central second harmonic peak at ~480 nm. By simply inserting a linear polariser plate in the laser beam, in front of the entrance slit of the spectrometer, we could deduce that the polarisation of all these blue-green signals was perpendicular to the fundamental wave polarisation. It follows that the nonlinear optical process should be a type-I ISHG[5].

The pure second harmonic generation at ~480 nm is much less intense than some of the "side-peaks" visible in the ISHG spectrum. The pure ISHG corresponds to a complete fulfilment of the phase-matching condition, with perfectly collinear propagation of the fundamental and second-harmonic waves, $\left(\theta_{1,2} \approx 0\right)$, whereas the generation of the pairs of "side-peaks" is determined by the existence of a non-negligible phase-mismatching in this second-order nonlinear process (four wave mixing process). In this context, the ISHG spectrum indicates that it is the phase-mismatching that prevails in the InGaAs/GaAs/AlGaAs waveguide region, rather than the conditions for perfect phase-matching.

Our explanation for the spectral distribution of the second harmonic emission is based on the vector diagram of momentum conservation, depicted as an inset to figure 1. If we denote by **k** the fundamental wave vector, by $\mathbf{k}_i$ – the wave vector of either "side-peak" in any pair of blue-green signals in the ISHG spectrum ($i = 1,2$), and by $\Delta\,\mathbf{k}_i$ – the corresponding phase-mismatch vector, then the vector expression of momentum conservation reads as:

$$\mathbf{k}_i - \left(\mathbf{k} + \mathbf{k}\right) = \mathbf{k}_i \neq 0, \tag{1}$$

The reciprocal cancellation of the phase-mismatch vectors of two such simultaneous interactions for which $\Delta\mathbf{k}_1 = -\,\Delta\mathbf{k}_2$ makes possible the emission of a pair of ISHG "side-peaks", with an energy conservation law of the form:

$$\omega_1 + \omega_2 - \left(\omega + \omega\right) - \left(\omega + \omega\right) = 0, \tag{2}$$

where ω is the angular frequency of the fundamental wave, while ω_i ($i=1, 2$) are the respective angular frequencies of the pair of "side-signals" in the ISHG spectrum. The several pairs of such "side-signals" that are distinguishable in the ISHG spectrum have different relative intensities. The most intense pairs can be assumed to correspond to the smallest possible angles θ between **k** and the corresponding $\mathbf{k}_i$'s.