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Highly nondegenerate four-wave mixing in a tunable dual-mode semiconductor laser

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We present experimental investigations of highly nondegenerate four-wave mixing in a tunable dual-mode semiconductor laser. The fundamental interacting waves are two lasing modes selected in an external double Littman–Metcalf cavity configuration. We investigate the conversion efficiency depending on the detuning frequencies up to 1.2 THz. We find that the newly generated waves are significantly enhanced due to the cavity resonances. Our investigations allow us to characterize and understand the dynamics of the simultaneous dual-mode operation in the semiconductor laser, which is attractive for the generation of continuous-wave THz radiation by photomixing. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1764604]

Dual-mode semiconductor lasers have recently found considerable interest for Terahertz (THz) wave generation by subsequent photomixing on antenna structures because of their compactness, stability, and cost efficiency.[1] But simultaneous dual-mode emission in the semiconductor laser also gives rise to nonlinear optical process, in particular intracavity nondegenerate four-wave mixing (NDFWM). In general, two primary optical waves at frequencies f_p and f_q copropagating in the active semiconductor medium induce a modulation of the gain and refractive index of the medium at the difference frequency $\Delta f = f_p - f_q$, which generates dynamic gain and index gratings. The primary waves are then scattered by the resulting dynamic gratings, and the new waves are generated at frequencies Δf apart from either side of the primary waves. The nonlinear mechanisms contributing to the NDFWM in semiconductor lasers and semiconductor optical amplifiers have been studied theoretically and experimentally by many groups[2–9] and have been identified as carrier density pulsation (CDP), carrier heating (CH), and spectral hole burning (SHB). NDFWM in a tunable dual-mode laser has not yet been studied systematically.

In this letter, we present experimental demonstration of highly NDFWM in a tunable dual-mode semiconductor laser. The experiment has been performed using a multiple quantum well (MQW) GaAlAs laser in an external double-cavity configuration. The interaction of the two modes in the laser medium induces newly generated waves. Both laser modes and the newly generated waves are resonant with the solitary[10] laser cavity mode. By discontinuously tuning the frequency difference of the two laser modes, we investigate the dependence of conversion efficiency on the detuning frequencies up to the THz range.

The highly[11] NDFWM has been studied in a commercial MQW GaAlAs laser diode (Hitachi HL7851G) operating at 785 nm and providing an output power of 50 mW. The laser has a high-reflective rear facet and a low-reflective front facet. The laser is driven at a pump current of $I_{\mathrm{pump}} = 4I_{\mathrm{thr}}$ ($I_{\mathrm{thr}} = 43$ mA) and the temperature is stabilized at room temperature. Figure 1 shows the experimental setup of the tunable dual-mode operation of the laser which is realized by spectrally filtered optical feedback from an external double-cavity configuration. The laser beam from the front facet is collimated by an antireflection-coated microscope objective and is incident on the diffraction grating (1200 grooves/mm), which is used for spectral selection. The first-order diffraction beam of the grating is coupled into the external double-cavity with a length of 40 cm. The beam is divided into two beams by a 50/50 beam splitter. Within each branch, we select the desired wavelength via tilting the external mirror which simultaneously controls the feedback strength. Consequently, the compound cavity system consists of the semiconductor laser resonator of length $L_{\mathrm{solitary}} \approx 670\ \mu$m and the external resonator. Therefore, the compound mode structure consists of the comb of the external cavity modes modulated by the solitary laser modes. The two modes which satisfy both resonator conditions can be tuned independently but only discontinuously over the whole gain bandwidth. The zeroth-order beam of the grating is used as output and is characterized using an optical spectrum analyzer with a resolution of 0.1 nm. For the study of the efficiency of highly NDFWM as a function of the frequency detuning, we kept the wavelength of one mode at 784.6 nm fixed close to the gain maximum and changed the wavelength of the other mode within the gain regime. For convenience, we here define the pump wave at f_p as the wave whose frequency is kept fixed close to the gain maximum and vary the wavelength of the probe wave at f_q.

Figure 2 shows an optical spectrum of the diode laser emission measured with the experimental setup of Fig. 1. We

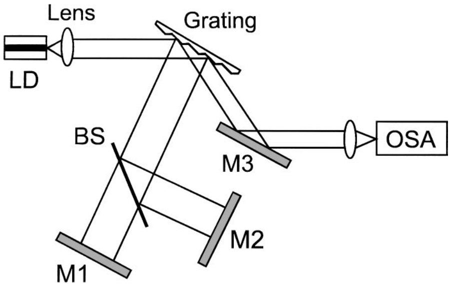

FIG. 1. Experimental setup: LD: Laser diode; BS: Beam splitter; M1, M2: External mirrors; M3: Mirror for output coupling; and OSA: Optical spectrum analyzer.

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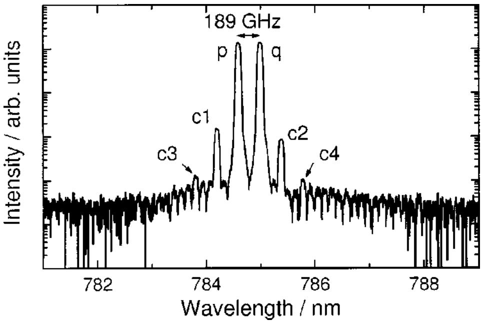

FIG. 2. Laser output spectrum of a cascaded FWM process. *p* and *q* are the dual laser modes; *c*1, *c*2, *c*3, and *c*4 are the newly generated waves.

see the two fundamental frequencies and a cascade of newly generated frequencies f_i with corresponding power P_i. First, we have verified by autocorrelation measurement that the two fundamental modes are indeed emitted simultaneously. In the time domain, this autocorrelation trace picture is equivalent to an ultrafast intensity modulation. Whether the nonlinearity and the power can also lead to modulation instability related phenomena has not been identified yet.[12] The simultaneous dual-mode operation of the laser *p* and *q* at frequencies f_p and f_q with a detuning frequency of $\Delta f = f_p - f_q = 189$ GHz results in the generation of new waves denoted as *c*1 and *c*2 at frequencies $f_{c1} = f_p + \Delta f$ and $f_{c2} = f_q - \Delta f$, respectively. We find additional waves *c*3 and *c*4 at frequencies $f_{c3} = f_p + 2\Delta f$ and $f_{c4} = f_q - 2\Delta f$ resulting from the interaction of the newly generated waves at f_{c1} and f_{c2} with the primary waves at f_p and f_q, respectively.[13] The newly generated frequencies are effectively amplified due to the high efficiency of the wave mixing process within the gain bandwidth of the laser and are enhanced by the laser cavity resonance.[14–16] Neglecting phase mismatching, which is justified in the present experiment,[7] where the maximum detuning frequency is 1.2 THz, the four-wave mixing (FWM) performance is even improved by increasing the interaction length due to reflection of the waves at the rear facet.[17,18]

Studying NDFWM at large detuning frequencies provides information on the characteristic mechanisms contributing to the nonlinear response of the medium to the optical field. One possibility to characterize the NDFWM process is the determination of the conversion efficiency extracted from the measured output power. The electric field $E(\omega_i)$ of the newly generated waves at frequencies $\omega_i \equiv 2\pi f_i$ is proportional to the induced polarization $\mathcal{P}(\omega_i)$ at frequencies ω_i which is related by the third-order susceptibility $\chi^{(3)}(\omega_i)$ to the electric fields $E(\omega_j)$, $E(\omega_k)$, $E(\omega_l)$ according to[19]

$$\mathcal{P}(\omega_i) = \epsilon_0 \chi^{(3)}(\omega_i) E(\omega_j) E(\omega_k) E * (\omega_l), \tag{1}$$

where the energy conservation $\omega_i = \omega_j + \omega_k - \omega_l$ has to be fulfilled. The normalized conversion efficiency $\eta(\omega_i)$ is then defined by the relation[20]

$$P(\omega_i) = \eta(\omega_i) P(\omega_j) P(\omega_k) P(\omega_l), \tag{2}$$

where $P(\omega_i)$ is the output power of the newly generated wave, and $P(\omega_j)$, $P(\omega_k)$, $P(\omega_l)$ are output powers of the primary waves. The conversion efficiency $\eta(\omega_i)$ is proportional to the square of the susceptibility $\chi^{(3)}(\omega_i)$.

Figure 3 shows the normalized conversion efficiency of the FWM process obtained in the experiment depending on the detuning frequency $|\Delta f|$ from 100 GHz up to 1.2 THz for positive detuning ($\Delta f > 0$) and up to 890 GHz for negative detuning ($\Delta f < 0$). For even higher detuning frequencies, the detectivity has been limited by noise. For positive detuning, η is nearly constant up to a detuning frequency of about 400 GHz and decreases for further detuning. For negative detuning, η decreases up to about 400 GHz and increases again for higher detuning. It approaches a nearly constant value as the detuning frequency increases above 600 GHz. In Figs. 3(a) and 3(b), we observe a similar behavior of η for the newly generated waves at frequencies of $f_{c1} = f_p + \Delta f$ and $f_{c2} = f_q - \Delta f$, respectively. However, in both images, there is an asymmetry of η between positive and negative detuning [i.e. (A) versus (B) in Fig. 3(a), (C) versus (D) in Fig. 3(b), respectively].

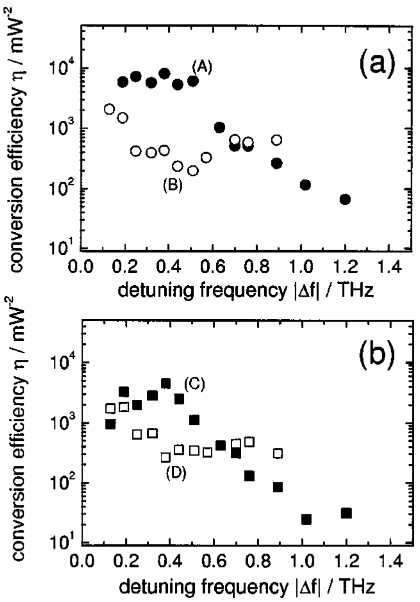

FIG. 3. Normalized conversion efficiency η depending on positive and negative detuning frequency: (a) $\eta = P_{c1}/P_p^2 P_q$: (A) for positive detuning (full circle), (B) for negative detuning (open circle); (b) $\eta = P_{c2}/P_p P_q^2$: (C) for positive detuning (full square), and (D) for negative detuning (open square).

CDP is the dominant mechanism contributing to FWM at detuning frequencies below 100 GHz.[7] For the generation of new waves at higher frequencies, where the carrier density cannot be effectively modulated, intraband processes, such as CH and SHB, are the dominant mechanisms. In particular, the observed asymmetry of the conversion efficiency between positive and negative detuning in Fig. 3 indicates that more than one mechanism is responsible for the behavior in this detuning range. We attribute this asymmetry to the interference of CDP, CH, and SHB mechanisms.[7,21] The interference between CDP and CH is almost symmetrical with respect to the sign of detuning, whereas CDP and CH interfere with SHB constructively for positive detuning and destructively for negative detuning. This interference between different mechanisms results in a less efficient conversion for negative detuning as compared to positive detuning as shown in Fig. 3(a).

It is worth noting from Fig. 3 that, although the two primary waves have almost the same output power, the conversion efficiency of the lower frequency (C) is slightly smaller than that of the higher frequency (A) for positive detuning. In contrast, for negative detuning the two waves show nearly the same conversion efficiency [(B) and (D)], independent of frequency. This smaller conversion efficiency of the lower frequency (C) compared to (A) in the case of positive detuning can be explained as follows. On the one hand, the amplification of the new frequencies is different depending on their position within the gain curve. On the other hand, depending on whether the pump wave lies in the vicinity of the gain peak or of the band gap, either CH or SHB is dominant.[22] Changes in carrier temperature hardly affect the carrier modulation in the region of the band gap; consequently, the effect of CH is of less importance as the probe wave approaches lower frequencies. Here, SHB is dominant. On the contrary, as the probe wave approaches higher frequencies, the effect of changes in carrier temperature is stronger and CH is present in addition to the SHB effect.

In conclusion, we have experimentally demonstrated highly NDFWM in a tunable dual-mode semiconductor laser realized by spectrally filtered optical feedback from an external double-cavity configuration. By tuning the frequency difference between the two modes, we have investigated the conversion efficiency depending on the detuning frequency of up to 1.2 THz. Its asymmetry depending on positive and negative detuning shows that CH and SHB are responsible for the nonlinear optical process over several hundred GHz range. Further quantitative studies, such as spectral and temporal analyses, should give more detailed insight into the dynamics of the simultaneous dual-mode operation in the semiconductor laser, which is attractive for the generation of continuous-wave THz-radiation by photomixing.

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