Nondegenerate Four-Wave Mixing in Quantum Dot Distributed Feedback Lasers

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***Abstract*—We present wavelength conversion using nondegenerate four-wave mixing in loss-coupled distributed feedback lasers based on InAs quantum dots (QDs) grown on a GaAs substrate. The conversion efficiency is measured to be −15 to −30 dB for a signal-pump detuning range from 0.33 to 8 nm. The third-order optical susceptibility $(\chi^{(3)})$ normalized to the optical linear gain in the QDs is estimated to be 3 $\times 10^{-20}$ m^3/V^2 to 9 $\times 10^{-20}$ m^3/V^2 for the signal-pump detuning range.**

***Index Terms*—Distributed feedback (DFB) lasers, four-wave mixing (FWM), quantum dot (QD).**

I. Introduction

FOUR-WAVE mixing (FWM) is a promising technique for wavelength conversion in communication systems and is typically realized in semiconductor optical amplifiers (SOAs) that require external pumping sources [1]. On the other hand, a single-mode distributed feedback (DFB) laser can be used as a simplified and integrated alternative with its counterpropagating lasing modes functioning as internal pumps [2]–[4]. Considering the uniformity of the wavelength conversion, FWM in gain- or loss-coupled DFBs suffers less from stopband effects but more from the strong cavity resonance compared to those in index-coupled DFBs [5]. Fortunately in real communication systems, wavelength channels are discrete and wavelength conversion can be enhanced by cavity resonance when the wavelength channels match the cavity modes. Quantum dots (QDs) have some fundamental advantages over quantum wells for nonlinear optics applications considering the theoretical $\chi^{(3)}$ enhancement by the quantum confinement in more dimensions [5], [6], ultrafast carrier recovery [7] and wide gain spectrum [8]. Although FWM in QD SOAs has been reported by different groups [9], [10], no FWM experiment in QD DFBs has yet been published. This letter reports the FWM and its cavity effects in a laterally loss-coupled (LLC) QD DFB.

II. Experimental Setup and QD DFB Characteristics

The experimental apparatus is presented in Fig. 1. Two LLC QD DFBs, Devices A and B, are used as a signal source and an FWM nonlinear medium, respectively. Two cascaded isolators and angle-polished single-mode fibers are employed to avoid external feedback into Device A. A fiber polarization controller is used to match the polarizations of the signal from Device A and the DFB mode of Device B. We find the FWM conversion efficiency varies sensitively as we adjust the fiber polarization controller, indicating the lasing modes in both QD DFBs are polarized. The FWM outputs are collected by a tapered-end fiber followed by an optical spectrum analyzer. The QD DFB is fabricated from an InAs–InGaAs QD structure with a first-order chromium metal grating deposited laterally to the etched waveguide ridge. The details of the material growth, processing, and optical performance can be found in previous publications [11], [12]. Except that the DFB mode is selectively enhanced by approximately 50 dB by the grating implemented in the devices, the QD LLC-DFB spectrum shows cavity-resonance modes similar to typical Fabry–Pérot devices. Based on the amplitude variation of the cavity modes of Device B, we find a weak stopband about 4 nm wide on the shorter-wavelength side of the DFB mode. This could be due to the index modulation associated with the loss grating in the DFBs. In this experiment, both devices are biased above threshold and have a sidemode suppression ratio better than 50 dB. Device A can be wavelength-tuned by about 8 nm using different combinations of heat-sink temperature and pump current. Even though this approach introduces variation of the signal power from Device A, it is notable that the FWM conversion efficiency, which is normalized to the signal power, is the parameter used to characterize the property of FWM nonlinear media. Device B is asymmetrically high-reflectivity coated on the facets of a 600-μm cavity. During the measurements, the wavelength and output power of Device B is fixed. Knowing the output power (7.4 mW) and facet reflectivities ($r_1 = 0.8$ and $r_2 = 0.95$) of Device B, we estimate the pump power for the FWM inside the cavity to be about 37 mW at 1307 nm.

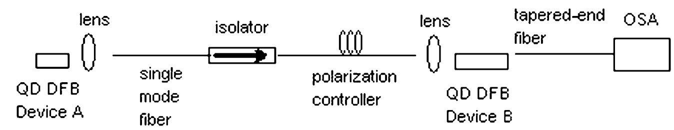

Fig. 1. Experimental setup for FWM in a LLC QD DFB (Device B).

III. Results and Discussion

The FWM in Device B is investigated over a wide spectral range, as shown in Fig. 2, which is an overlapped spectrum of 21 FWMs with different signal-pump detunings. For each data

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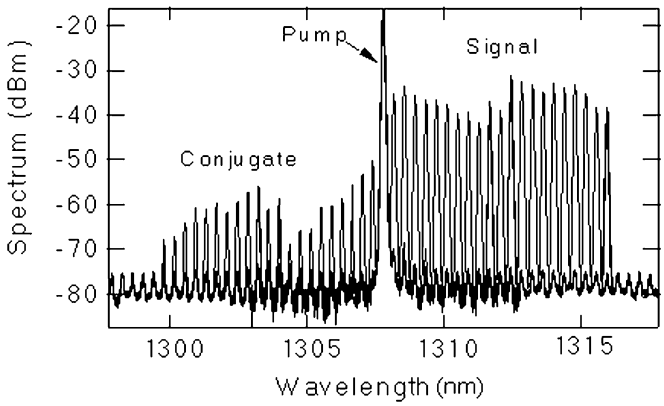

Fig. 2. Plot of the optical emission spectrum of Device B with 20 signals detuned differently from the pump wavelength. The FWM efficiency is maximized for each detuning value by lining up the conjugate beam with the cavity mode.

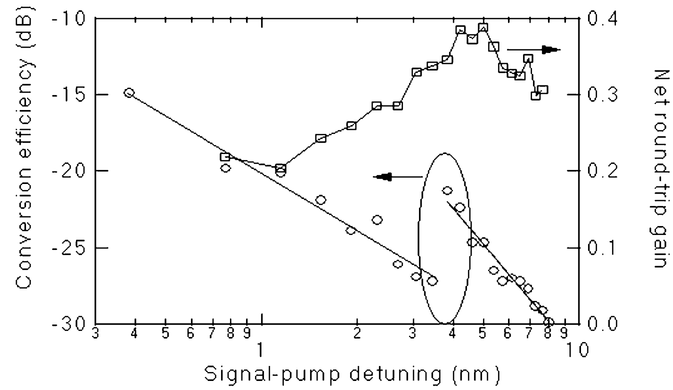

Fig. 3. FWM conversion efficiency with maximum cavity enhancement versus the detuning in the spectrum presented in Fig. 2. The net round-trip gain is obtained from the optical emission spectrum without FWM using the Hakki–Paoli technique.

point, the signal wavelength is carefully tuned so that the FWM conversion efficiency is maximized by lining up the conjugate beam with the cavity resonances. The FWM conversion efficiency drops by 3 dB when the wavelength of the signal beam is tuned 0.05 nm away from the position of the maximum conversion efficiency, which corresponds to a conversion bandwidth of 9 GHz at 1307 nm. The locally maximized conversion efficiency varies from -14 to -30 dB when the detuning increases from 0.33 to 8 nm, or 60 GHz to 1.4 THz. To estimate the nonlinear susceptibility $(\chi^{(3)})$, we simply employ the traveling-wave approximation, following the case in [3], to describe the propagation of the FWM conjugate beam inside a semiconductor laser

$$\frac{dE_{\mathrm{conj}}}{dz} = \frac{\Gamma g}{2}E_{\mathrm{conj}} + i\frac{3\Gamma\mu_0\varepsilon_0\omega^2}{8k_0 n}\chi^{(3)}E_{\mathrm{pump}}^2 E_{\mathrm{sign}} \quad (1)$$

where E_{conj}, E_{sign}, and E_{pump} are the field amplitudes of the conjugate, signal, and pump beam, respectively, k_0 is the wave vector of the conjugate light in vacuum, ω is the optical angular frequency of the conjugate beam, n is the refractive index, Γ is the optical confinement factor, $\chi^{(3)}$ is the third-order optical susceptibility, g is the net material gain of the QD gain medium, L is the cavity length of the FWM device, and z is the spatial displacement along the propagation direction. Rearranging (1) to reflect that the second term on the right-hand side is a constant yields

$$\frac{d\left(E_{\mathrm{conj}} + i\frac{3\Gamma\mu_0\varepsilon_0\omega^2}{8k_0 n}\chi^{(3)}E_{\mathrm{pump}}^2 E_{\mathrm{sign}}\right)}{dz} = \frac{\Gamma g}{2}\left(E_{\mathrm{conj}} + i\frac{3\Gamma\mu_0\varepsilon_0\omega^2}{8k_0 n}\chi^{(3)}E_{\mathrm{pump}}^2 E_{\mathrm{sign}}\right). \quad (2)$$

Integrating (2) from $z = 0$ to $z = L$ and applying the travel-wave boundary condition $E_{\mathrm{conj}} = 0$ at $z = 0$, we can get an expression for the FWM conversion efficiency

$$\eta = \left|\frac{E_{\mathrm{conj}}}{E_{\mathrm{sign}}}\right|^2 = \left|\frac{3k_0}{4n}\Gamma\chi^{(3)}E_{\mathrm{pump}}^2\frac{\exp\left(\frac{\Gamma gL}{2}\right)-1}{\Gamma g}\right|^2. \quad (3)$$

Given $L = 600\ \mu$m, the internal-cavity optical pump power of 37 mW, the effective mode area of 1.47 μm^2, and a conservative Hakki–Paoli estimate of the net round-trip gain of Device B presented in Fig. 3, the ratio of the third-order optical susceptibility $\chi^{(3)}$ to the material gain coefficient g_0 is estimated to be 3–9 $\times\ 10^{-20}$ m^3/V^2 within the signal-pump detune range of 0.33–8 nm based on (2). This result is consistent with the order of the 1.9 $\times\ 10^{-20}$ m^3/V^2 result published by Akiyama *et al.*, in QD SOAs [13].

In the conversion efficiency plot of Fig. 3, two different regimes are found relative to the signal-pump detuning: for 0.3–3.3 nm, the slope is about -1.2 while for 4–8 nm about -2.4. Theoretically, the slope should be close to -2 since $|\chi^{(3)}|^2$ has a Lorentzian functional dependence on the frequency detuning [3], [13]. In the DFB laser case, cavity resonance and the variation of the optical gain across the detuning range should be considered to explain the discrepancy between theory and experiment. Applying the Hakki–Paoli technique [14] to the optical emission spectrum of Device B, we find that the net round-trip gain, defined as $r_1 r_2 \exp(2\Gamma gL)$, increases as the detuning changes from 0.3 to 3.3 nm and decreases in the region from 4 to 8 nm. These gain data are summarized in Fig. 3. As seen from the results, an increasing gain toward 3.3-nm detuning indicates a stronger cavity enhancement that improves FWM efficiency and *vice versa* for the 4–8 nm range. Thus, these observed trends qualitatively explain the power-law dependence of the conversion efficiency on detuning. It is believed that the nonconstant distribution of the net gain in the device results from the DFB stopband and might also come from the spectral hole burning effect which is believed to be significant in QDs [15]. The discontinuity around 4 nm cannot be simply explained by the gain behavior estimated from the Hakki–Paoli method and could be attributed to crossing over the stopband [16] mentioned in Section II.

IV. Conclusion

The first results on FWM in a QD LLC DFB laser at 1307 nm are reported in this letter. The conversion efficiency is found to change from -14 to -30 dB for a detuning range from 60 GHz to 1.4 THz and the value of $\chi^{(3)}/g_0$ is estimated to be 3–9 $\times$

10^{-20} m^3/V^2 in the QD gain medium for a signal-pump detune range from 0.33 to 8 nm. The conversion efficiency is found proportional to $(\Delta\lambda)^{-1.2}$ in the detuning range of 0.3–3.3 nm and to vary as $(\Delta\lambda)^{-2.4}$ from 4 to 8 nm, which is attributed to the cavity resonance and the net gain nonuniformity due to the residual stopband from the grating and probably the spectral hole burning effect in the QD DFB.

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