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**Implementation of efficient transversely-pumped counter-propagating
optical parametric amplifiers and difference-frequency generation**

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Brief Summary

Our objective is to eventually generate and amplify mid-IR waves based on GaAs/AlGaAs multilayers in a transverse-pumping geometry. Within the funding period, we have successfully set up and tested an OPA pumped by a Regenerative Amplifier. We have recently designed and grown a new multilayer structure for efficiently generating 2.66 μm by mixing 1.55 μm and 980 nm in a transverse-pumping geometry. Experimentally, we have observed high-order phase-matching peaks for second-harmonic generation in GaAs/AlAs multilayers in reflection geometry and confirmed quadratic dependence of the second-harmonic pulse energy on pump pulse energy for the first time.

We will continue to work towards our eventual goal, which will make long-lasting and dramatic impact on optical communications, and can be eventually used for counter measure, remote sensing, spectroscopy, and optical signal processing.

Achievements for the covered period

Within the funding period, we have been working on several aspects of the proposed project. In this report, I will highlight our achievements.

1. Accomplishment of setting up RegA and OPA system

After receiving this grant, we had purchased Coherent RegA 9000, which is a Ti:Sapphire Regenerative Amplifier. We have upgraded our Argon laser for producing a maximum output power of 25 Watts. We have used our Argon laser to pump both Ti:Sapphire oscillator (Mira 900) and RegA 9000 with the Argon-laser output power split as 8W/12W. We have then used the output beam from our RegA with the power of 800 mW at 800 nm to pump OPA 9800 with its output wavelength in the range of 1.1-2.4 μm . The entire system costs us \$156,000 and is quite complicated. It consists of four cavities. It was finally installed and became operational several months ago. Since then, we have worked on it day and night to align and fine-tune this system. We have just tested the performance of our OPA 9800. We are now completely satisfied by the system.

In order to test our OPA system, we have used it to study cascaded second-harmonic and sum-frequency generation in Ce-doped KTP. For the first time, we have observed unique features on the dependence of the third-harmonic power on the input power [1].

- [1] X. Mu, X. Gu, and Y. J. Ding, "Frequency-tripling of 1.32- μm beam in a single Ce-doped KTP using subpicosecond laser pulses," submitted to Opt. Lett.

2. Design and growth of new multilayer structure for generating 2.66 μm by mixing 1.55 μm with 980 nm

Several years ago, we proposed to use transversely-pumped counter-propagating optical parametric oscillators and amplifiers (TPCOPOs and TPCOPAs) to efficiently generate and amplify mid-IR beams [1]. The advantage of this novel configuration is the large tuning range achieved by changing the propagation direction of the pump [2]. Furthermore, the devices are miniature and ultrastable since they do not require any cavity to achieve oscillation. Recently, we have successfully grown a multilayer structure. It can be used to amplify the input beam at 1.58 μm and to generate a new beam at 3.23 μm if a pump at 1.064 μm is present [3]. As a first step, we have characterized this structure based on reflection-second-harmonic generation, as presented in the next section.

Due to rapid development of erbium-doped fiber and diode lasers, we have designed and grown a new multilayer structure as shown in Fig. 1. This device can be used to amplify the input beam at 1.55 μm and to generate a new, 2.66- μm beam in the present of a pump beam at 980 nm. This structure can be eventually integrated with a vertical-cavity surface-emitting laser (VCSEL). As a result, the pump beam inside the multilayers can be provided via current injection in a VCSEL.

We are currently characterizing this structure. Our results will be presented at the 1999 OSA Ann. Meet.

- [1] Y. J. Ding, S. J. Lee, and J. B. Khurgin, Phys. Rev. Lett. 75, 429 (1995).
 [2] Y. J. Ding, J. B. Khurgin, and S. J. Lee, IEEE J. Quantum Electron. 31, 1648 (1995).
 [3] Y. J. Ding and J. B. Khurgin, J. Opt. Soc. Am. B 14, 2161 (1997).

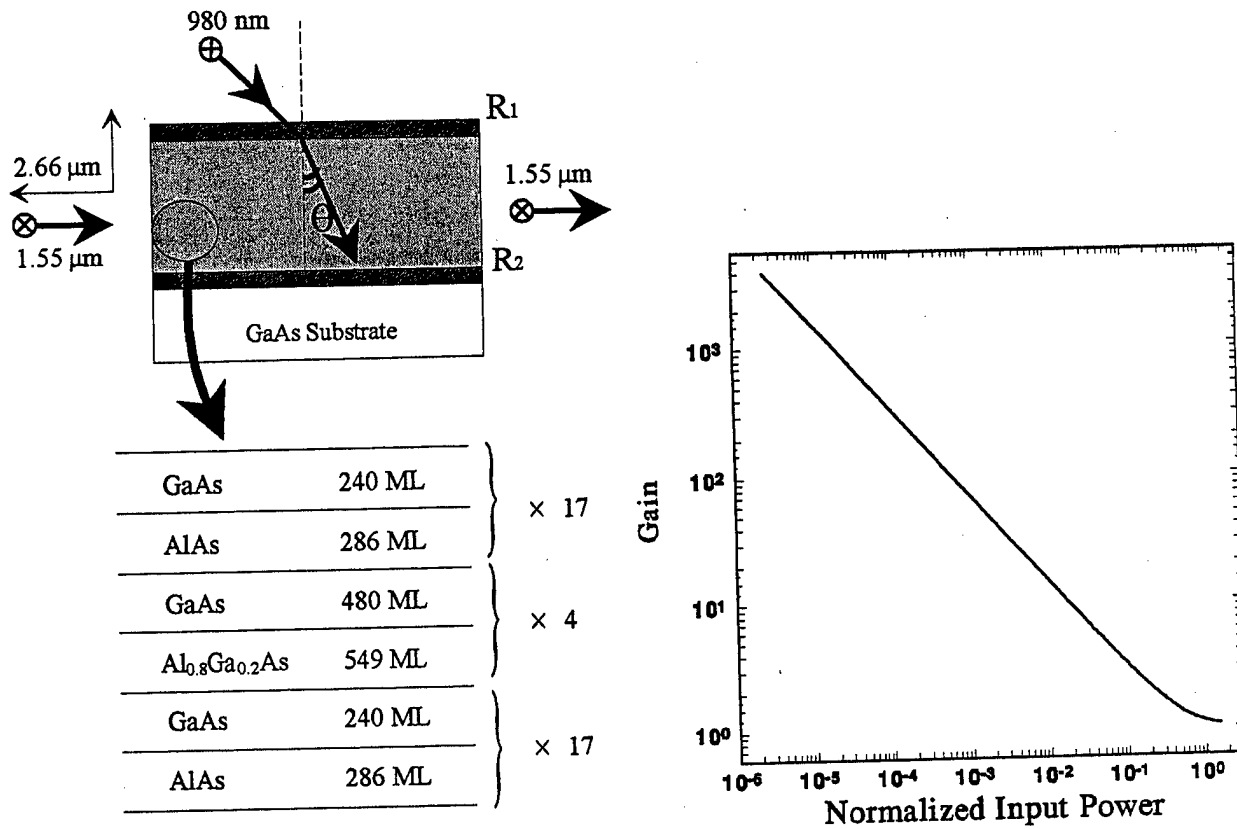


Fig. 1 Left: a new multilayer structure just designed and grown in collaboration with NRL. This device can be used to amplify 1.55 μm and to generate 2.66 μm by mixing 1.55 μm with 980 nm. Right: expected dependence of the gain for the 1.55-μm input beam on the input power normalized by the threshold for oscillation.

3. First observation of high-order quasi-phase-matched second-harmonic generation in GaAs/AlAs multilayers in reflection geometry

In this section, we report our first results on observation of high-order phase-matching peaks for second-harmonic generation in GaAs/AlAs multilayers in reflection geometry and confirmed quadratic dependence of the second-harmonic pulse energy on pump pulse energy for the first time.

GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ possess large magnitude of second-order nonlinear susceptibilities. By integrating with commercialized diode lasers, it is possible to eventually fabricate monolithic devices for efficiently generating coherent visible light, especially in the blue-green [4] and mid-IR [5] domains via parametric processes. However, because these materials have negligible birefringence, multilayers have to be used for quasi-phase-matching (QPM). There are two configurations for achieving QPM: surface-emitting [4,5] and reflection [6,7]. Reflected second-harmonic generation (SHG) in periodic multilayer GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ was initially studied in Ref. [6] and later in Ref. [7]. However, QPM peak was not clearly identified in Ref. [6] since the obtained spectrum is extremely broad. On the other hand, QPM peak was not directly measured in Ref. [7]. Upon the detailed examination of Refs. [6,7], we believe the pump wavelength is near the first-order QPM region in both cases. Here we report our results on detailed investigation of SHG in reflection geometry ("reflection-SHG") in GaAs/AlAs multilayer. For the first time, we measured the spectra of the reflection-SHG and identified high-order QPM peaks. Moreover, we confirmed the quadratic dependence of the SH pulse energy on the pump pulse energy. Fig. 2 shows the structure of our sample. 15 pairs of alternating GaAs/AlAs layers were grown by Molecular-Beam Epitaxy. The thicknesses of each GaAs and AlAs layers are 806 Å and 955 Å, respectively. They were chosen for achieving transversely-pumped counter-propagating optical parametric amplification (TPCOPA) and difference-frequency generation (DFG) with a specific set of wavelengths [8]. A nanosecond laser pulse with tunable output wavelength was used in our measurement. We first measured the reflection-SHG spectra within 950 - 1220 nm at different incident angles ranging from 23° to 65°. Fig. 3 is an example at 30°. In the measured wavelength range, three obvious peaks were found as shown in Fig. 3. Based on the QPM condition for the reflection-SHG, we have assigned peaks A and C to the QPM reflection-SHG with $m = 2$ and 3, respectively. We would like to stress that this is the first time to directly measure QPM reflection-SHG peaks in multilayers. The pump wavelength required to observe the first-order QPM peak is beyond the tuning range of our laser. On the other hand, certain peaks can be produced in the reflection direction for the SH beam by Distributed Bragg Reflection (DBR). Peak B in Fig. 3 is attributed to DBR at the first order. We also measured the dependence of the SH pulse energy on the pump energy per pulse. Fig. 4 is an example for Peak C at 23°. One can see that our data exhibit a clear quadratic dependence. However, such a dependence was not confirmed previously in Refs. [6,7]. We have determined the conversion efficiency to be about $1.8 \times 10^{-9}\%$ at a peak pump intensity of 1.64 MW/cm^2 . It is low because the generated SH beam is partially absorbed by the AlAs layers. We have re-designed the thicknesses and aluminum concentration of the layers to reduce absorption and to include a vertical cavity for the enhancement of conversion efficiency. We are in the process of measuring conversion efficiency on the optimized structure, and achieving TPCOPA and DFG. Besides the potential application for frequency-doubling, the reflection-SHG can be used to accurately determine indices of refraction above bandgaps of semiconductors for the first time as well as aluminum concentration and layer thickness.

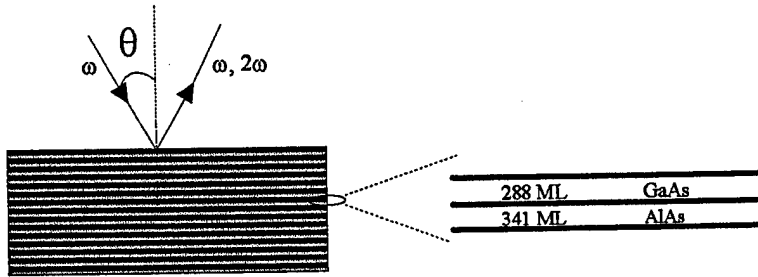


Fig. 2 Structure of the GaAs/AlAs multilayers.

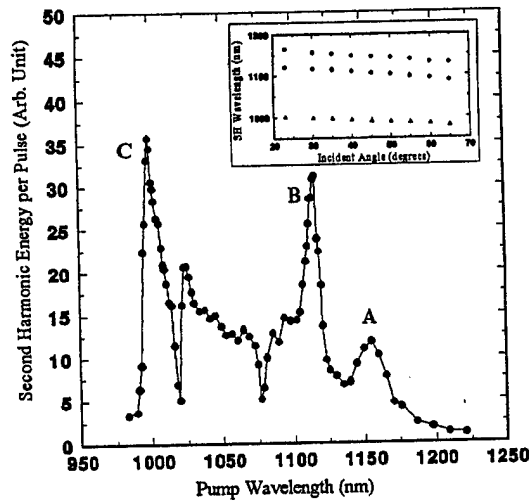


Fig. 3 Reflection-SHG spectrum at incident angle of 30°. Inset: Reflection-SHG peak wavelengths vs. incident angle. Filled circles: Peak A, open circles: Peak B, filled triangles: Peak C.

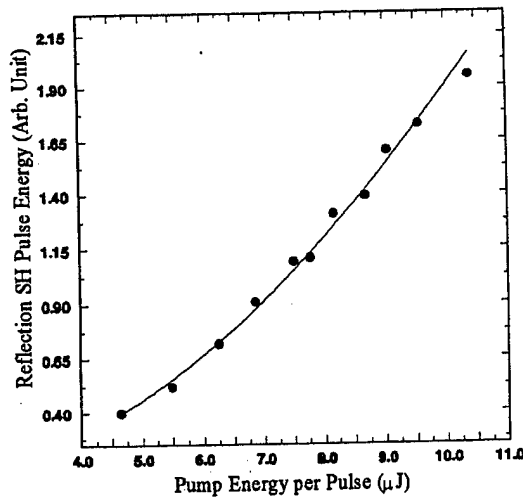


Fig. 4 Dependence of the SH pulse energy vs. pump energy per pulse. Filled circles: experimental results. Solid line: least-square fitting. Our data exhibit a clear quadratic dependence.

As a result, we have submitted one paper to Opt. Commun. and presented our results at CLEO'99 and Quantum Optoelectronics'99.

- [4] R. Normandin, R. L. Williams, and F. Chatenoud, *Electron. Lett.* **26**, 2088 (1990).
- [5] Y. J. Ding, J. B. Khurgin, and S. J. Lee, *IEEE J. Quantum Electron.* **31**, 1648 (1995).
- [6] J. P. van der Ziel and M. Ilegems, *Appl. Phys. Lett.* **28**, 437 (1976).
- [7] S. Janz, C. Fernando, H. Dai, F. Chatenoud, M. Dion, and R. Normandin, *Opt. Lett.* **18**, 589 (1993).
- [8] Y. J. Ding and J. B. Khurgin, *J. Opt. Soc. Am. B* **14**, 2161 (1997).

Future work by using this new system

In the future, we will continue to investigate transversely-pumped counter-propagating optical parametric oscillators and amplifiers to efficiently generate and amplify mid-IR beams, especially at the 1.55- μm region for optical communications.

Publications of Yujie J. Ding for the covered period

Conference Proceedings

Y. J. Ding and J. B. Khurgin, "Large optical parametric amplification and efficient difference-frequency generation in transverse-pumping geometry," in *Applications of photonic technology 3: closing gap between theory, development, and application*, G. A. Lampropoulos, R. A. Lessard, Editors, Proceeding of Proc. Vol. 3491, 201-208 (1998).

Y. J. Ding and J. B. Khurgin, "Surface-emitting second-harmonic generation from short laser pulses," in *Ultrafast phenomena in semiconductors II*, Kong Thon Tsen, Harold R. Fetterman, Editors, Proceedings of SPIE Vol. 3277, 226-237 (1998).

Conference Presentations

[(*) - refereed papers; (**) - invited papers]

** Y. J. Ding and J. B. Khurgin, "Efficient backward harmonic generation in second-order nonlinear media," 4th Mediterranean workshop and topical meeting, "Novel optical materials and applications", Jun. 4-10, 1999, Cetraro, Italy.

* X. Gu, Y. J. Ding, W. S. Rabinovich, D. S. Katzer, and J. B. Khurgin, "First observation of high-order quasi-phase-matched second harmonic generation in semiconductor multilayers in reflection geometry," QELS'99, Paper QThL2, May 23-28, Baltimore, MD.

* X. H. Gu, Y. J. Ding, J. B. Khurgin, W. S. Rabinovich, and D. S. Katzer, "First observation of high-order quasi-phase-matched second-harmonic generation in semiconductor multilayers in reflection geometry," Spatial Light Modulators meeting, Apr. 12-16, 1999, Aspen, CO.

V. T. Petrov, Y. J. Ding, and J. B. Khurgin, "Parametric amplification of short laser pulses in transverse-pumping geometry," Paper ThBBB3, OSA Ann. Meet. '98/ILS-XIV.

* Y. J. Ding and J. B. Khurgin, "Large optical parametric amplification and efficient difference-frequency generation in transverse-pumping geometry," 1998 Intern. Conf. Appl. Photon. Tech., July 27-30, 1998, Ottawa, ON, Canada, Paper ICAPT98T60.

Pending Publications

Y. J. Ding, "Parametric amplification of short pulses in transverse-pumping geometry," submitted to JOSAB.

X. Gu, Y. J. Ding, W. S. Rabinovich, and D. S. Katzer, "Observation of reflection-second-harmonic generation in GaAs/AlAs multilayers," submitted to Opt. Commun.

X. Mu, X. Gu, and Y. J. Ding, "Frequency-tripling of 1.32- μm beam in a single Ce-doped KTP using subpicosecond laser pulses," submitted to Opt. Lett.