博士論文公聴会の公示（物理学専攻）

学位申請者	PHAN THANH NHAT KHOA
論文題目	Harmonic Generation from Narrow Gap Semiconductors in the Terahertz Region テラヘルツ領域におけるナローギャップ半導体からの高調波発生
日時	2024 年 8 月 7 日（水） 16:50 – 18:20（5 限目）
場所	特例としてオンラインにより行う（大学院教育教務委員承認済み） URL 等については学内の方は下記を参照。 https://www.phys.sci.osaka-u.ac.jp/naibu/info/detail.php?id=9117 学外の方は主査：藤岡（fujioka.shinsuke.ile[at]osaka-u.ac.jp [at]=@）に問い合わせること。
主査	藤岡 慎介
副査	工藤 一貴、木村 真一、千徳 靖彦、有川 安信、中嶋 誠

The terahertz (THz) electromagnetic region, which covers the frequency range from 0.3 THz to 10 THz, has been received quite a fair amount of interest due to high potential of applications such as the advent of wireless communication systems of the sixth generation (6G network), security and bio-medical imaging, data storage media, air pollution diagnosis with THz time-domain spectroscopy (THz-TDS) and fusion plasma diagnosis. These applications involve the generation and detection of new frequency, e.g. the nonlinear optical process of harmonic generation. However, the advances of nonlinear optics in the THz region have been less than the near infra-red (NIR), visible (VIS) region and the microwave region, thus this spectrum region has been dubbed “the terahertz gap”. The reasons of which include the lack of adequately intense pump source, the strong absorption of various gas species in the earth atmosphere which limits the propagation distance to less than~10 meters, to name a few.

The issue about lacking of adequately strong THz pump source has recently seen significant progress through several novel techniques, including the femtosecond laser based optical rectification (OR) system and free electron laser (FEL). The FEL has several advantages when harmonic generation and detection are involved, including intense electric field (around MV/cm), a narrow frequency bandwidth, strong coherence, short pulse duration (as small as several picoseconds). The interesting point of this laser characteristic, especially the intense electric field, is that it is not only highly capable of generating a harmonic signal with high conversion efficiency, but it can also push the electron system of the narrow bandgap semiconductor into a non-perturbative regime, where a vast variety of other

nonlinear ultrafast phenomena come into interplay.

By utilized the merits mentioned above in the FEL at the Sanken facility in Osaka University, we studied the third harmonic generation (THG) in the THz region from indium antimonide (InSb), indium arsenide (InAs) and silicon (Si) [1, 2]. InSb and InAs serve as the stereotype of the famous narrow bandgap semiconductor, whose free carriers possess a high third order susceptibility due to the non-parabolicity (NP) of the conduction band. This non-parabolicity contributes essentially to the THG in THz region in our samples. We report a high THG efficiency which was optimized to a value which, to the best of our knowledge, is the highest ever reported so far in the THz region, higher than even those of the novel materials such as graphene and topological insulators. This is the result of the combination between the merits of the FEL and the tuning of the density and mobility of the free carrier in the samples.

In the subsequent part of our research, the THG due to the momentum-dependent scattering rate (SC) was conducted and we obtained the complex anisotropy ratio, which is the ratio between the elements in the THG susceptibility tensor [3]. This is, to the best of our knowledge, the first research ever reported regarding a complex nonlinear susceptibility in the FIR-THz gap of the electromagnetic spectrum. The imaginary part of the complex nonlinear susceptibility can be ascribed to the momentum-dependent scattering rate of the free carrier. This result can be helpful for researchers who are in pursuit of gaining better understanding about scattering-related ultrafast events in the picosecond time scale.

Refernce

[1] T. N. K. Phan, K. Kato, G. Isoyama, M. Yoshimura, S. Fujioka, M. Nakajima, ”Third Harmonic Generation From InSb Excited By Free Electron Laser”, 43rd International Conference on Infrared, Millimeter and Terahertz Waves (**IRMMW-THz 2018**), 8509972 (2018).

[2] T. N. K. Phan, T. Shimizu, Y. W. Wang, K. Kato, V. C. Agulto, G. Isoyama, S. Fujioka, and M. Nakajima, “Third harmonic generation due to free carrier in InSb using a terahertz free electron laser,” Opt. Lett. **49**, 1073 (2024).

[3] T. N. K. Phan, Y. W. Wang, T. Shimizu, K. Kato, V. C. Agulto, G. Isoyama, S. Fujioka, and M. Nakajima, “Complex anisotropy ratio of third harmonic generation in semiconductor using terahertz free electron laser”, Opt. Lett., submitted.