Efficient High-Power Tunable Terahertz Sources based on Intracavity Difference Frequency Generation

Patrick Tekavec[a], Walter C Hurlbut[a], Vladimir G Kozlov[a], and Konstantin L Vodopyanov[b]
[a]Microtech Instruments, Eugene, Oregon, 97401, USA
[b] Stanford University, Stanford, California, 94305 USA

***Abstract*—We demonstrate tunable (0.8-2.8 THz) narrow-band THz waves using fiber-laser pumped ring cavity, near-degenerate type 0 or type II PPLN OPO's. Over 130 µW (120 µW) of stable CW THz waves were generated at 1.5 (0.8) THz in a periodically-inverted gallium arsenide sample using intracavity difference frequency generation with the type 0 (II) OPOs.**

I. Introduction And Background

First demonstrated in 1965, photonic generation of THz radiation via frequency down conversion in electro-optic crystals is an attractive way to produce THz waves[1]. However, optical-to-THz conversion efficiency is typically less than 10^{-5}. Resonant cavity enhancement of the optical waves is one method to circumvent this problem. In previous work[2], a GaAs crystal with a quasi-phase-matched (QPM) structure was inserted inside the cavity of a near-degenerate doubly-resonant type-II-phase-matched OPO pumped by a high-power (10W) picosecond laser and. Up to 1 mW of THz pulsed power was generated by intracavity difference frequency mixing between the signal and idler waves. In fact, by resonant enhancement of both optical waves in a cavity with a finesse $\mathcal{F}$ ($\mathcal{F}$~50-100), one can increase the optical-to–THz conversion efficiency by a factor of $\mathcal{F}^2$.

Using a ring (instead of linear) OPO cavity with much higher finesse, switching between type-0 and type-II PPLN crystals as the gain medium resulting in a low OPO threshold, and a compact fiber laser pump, we demonstrate significant improvements in stability and control of THz waves generated using this approach.

II. RESULTS

In the type 0 OPO, 6.7 W of pump power generated greater than 100 W of intracavity power. An 11 layer GaAs crystal with a QPM structure designed for 1.5 THz power production assembled by optical contacting (OC-GaAs) was placed at the second focal plane in the OPO and generated 132 µW of CW THz average power[3]. When optimally generating THz waves, the mid IR spectrum consisted of two pairs of signal and idler circulating simultaneously. However, the broad acceptance bandwidth of the type 0 OPO allows fluctuations between several sets line pairs, making it difficult to stabilize. The advantage of the type II cavity is that it has a much smaller acceptance bandwidth than the type 0 cavity, and will only produce oscillation for a single line pair.

The type II double resonant ring cavity OPO is shown in figure 1. The OPO is pumped at 1064nm with 5W of 6 ps pulses and 109 MHz rep rate from the output of a fiber laser (Fianium). In the type II OPO, the signal and idler beam are orthononally polarized, and the birefringence of the PPLN gain crystal must be compensated for to achieve equal paths length needed for double-resonance. This is done with litium niobate blocks inserted in the cavity, oriented so the birefringence is opposite that of the gain crystal. Fine tuning of the overall path length is done with a mirror mounted on a piezo-electric transducer. THz radiation is generated by difference frequency generation (DFG) between signal and idler pulses by placing a quasi-phasematched sample of GaAs at a second focal point in the cavity; the signal and idler frequency separation are tuned to the QPM wavelength of the crystal by temperature tuning the PPLN. The THz radiation is collected with an off-axis parabolic mirror inserted in the cavity, and detected with a Golay cell.

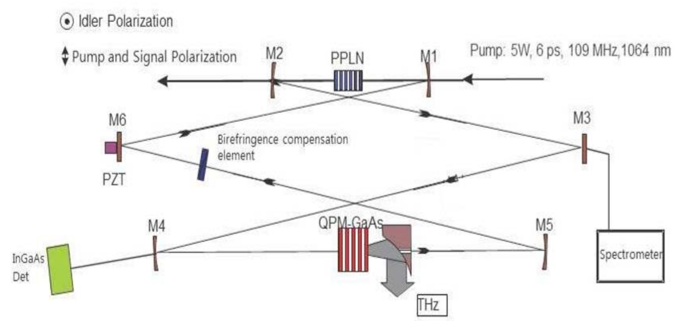

Figure 1: Schematic of the type II DR-OPO used for intracavity THz generation.

The inherent instability of a DR-OPO requires the path length to be stabilized to less than a micron in order for both signal and idler to be resonant. This is also necessary for stable quasi-CW THz output. A feedback circuit can be used to lock the cavity to a single signal/idler pair. Additionally, the insertion of GaAs into the cavity acts to thermally self-stabilize the cavity; using this method we have achieved stable CW THz output of greater than 100 µW for periods of up to 10 minutes.

In figure 2 we show the THz spectrum produced from a 4-layer OC-GaAs sample and measured with a Michelson interferometer. The center frequency is 860 GHz, which is in good agreement with the 780 GHz expected from the 2mm QPM period of the sample. The THz bandwidth is 70 GHz, which is narrow enough to fit into the atmospheric transmission window at 850 GHz.

978-1-4577-0509-0/11/$26.00 ©2011 IEEE

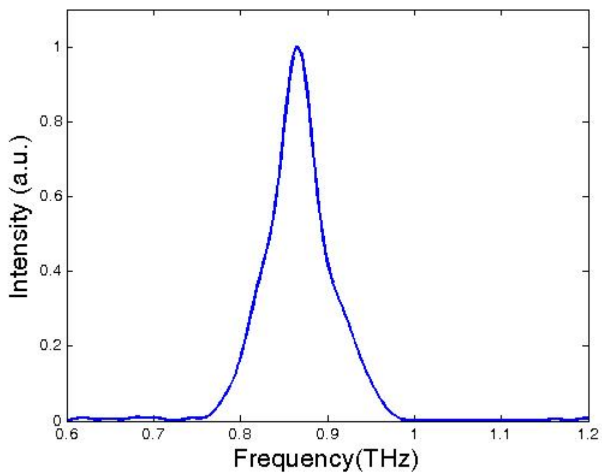

Figure 2: Spectrum of THz output generated in type II OPO using 4 layer OC-GaAs.

120 μW of THz with 77 W intracavity power achieved with a 4-layer OC-GaAs sample that had a QPM period optimized for 780 GHz. The measured optical to THz conversion efficiency is 3.1×10^{-6}. Calculating the expected conversion efficiency using the theory of Vodopyanov[4], we obtain 6.5×10^{-6}, which is only about a factor of 2 greater than the measured efficiency. The use of samples with QPM periods designed for higher frequencies and the use of longer samples should lead to increased THz efficiencies. Additionally, increasing the intracavity power (by increasing the pump power) will give higher THz powers.

With a 4-layer layer sample of optically contacted Gallium Arsenide (OC-GaAs) in the cavity, the threshold for oscillation is 550 mW, which is only 100 mW increase form the 450 mW threshold for an empty cavity (no GaAs sample). The intracavity power scales linearly with the pump power reaching 77 W at 5 W pump power. In figure 3, we show the dependence of the THz power as a function of intracavity power on a log scale. A linear fit gave a slope of 1.8, which is close to expected quadratic scaling. This scaling, along with the fact that there is no point of THz power saturation, means that a great increase in THz power can be achieved with a modest increase in pump power.

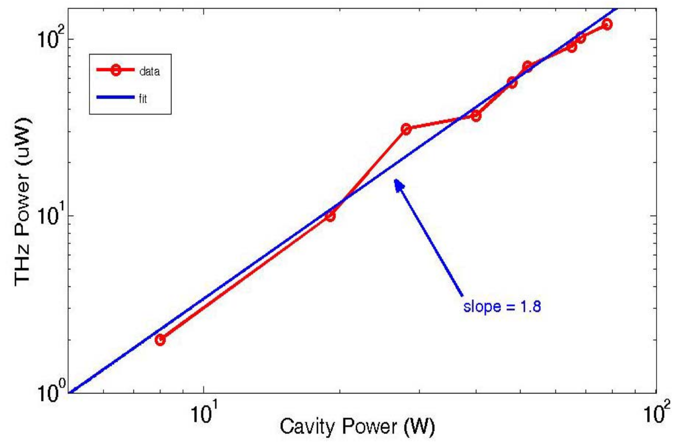

Figure 3: Log Plot of THz power vs. Intracavity Power. Data (red) along with linear fit (blue).

III. CONCLUSION

We have demonstrated a stable, high average power (>100 μW) continuous wave THz source based on intracavity DFG in QPM GaAs. The use of different QPM periods enables tuning of the THz frequency across a broad range of frequencies, including the 900 GHz and 1.5 THz atmospheric transparency windows. A combination of high pump power, longer samples, and higher THz frequencies will allow us to reach mW levels of continuous wave THz power. tuned to 900 GHz and 1.5 THz atmospheric transparency windows. Such a source will be superior to current electronic and laser sources due to higher power and excellent beam characteristics, potentially enabling next generation of portable THz imaging systems. This latest result opens a clear path for implementation of a commercially available DFG based THz source.

This STTR project was funded by AFOSR contract number FA9550-10-C-0021.

REFERENCES

[1] F. Zernike, Jr. and P. R. Berman, "Generation of far infrared as a difference frequency," Phys. Rev. Lett., vol. 15, pp. 999–1002, 1965.

[2] J. E. Schaar, K. L. Vodopyanov, M. M. Fejer, "Intracavity terahertz-wave generation in a synchronously pumped optical parametric oscillator using quasi-phase-matched GaAs", Opt. Lett. **32**, 1284 (2007).

[3] K. L. Vodopyanov, W. C. Hurlbut,, V. G. Kozlov, "Photonic THz generation via resonantly-enhanced intracavity multispectral mixing", accepted for publication in App. Phys. Lett.

[4] K. L. Vodopyanov," Optical generation of narrow-band terahertz packets in periodically-inverted electro-optic crystals: conversion efficiency and optimal laser pulse format", Opt. Exp. **14**, 2263 (2006)