

Report to AOARD

Title

Development of high efficient, compact, robust and tunable IR and Terahertz light sources
using periodically polled frequency conversion devices

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14. ABSTRACT A tunable IR wavelength conversion device using quasi-phase-matched (QPM) optical parametric generation was optimized for wavelength, compactness and environmentally less sensitive. Although the IR light source can be applied for various fields, the research was targeted toward dental surgical applications for the removal of hard enamel, dentine and bone tissues and at the same time developing a new capability for use in other tunable IR laser research and applications to interfacial media and biological sciences. The project goals consisted of: (1) setting up the polarization switching system to fabricate QPM devices, (2) assembling the Mg: stoichiometric lithium tantalate based QPM devices, (3) setting up a new experimental capability to generate tunable light around 2.78&#956;m by the OPO system, (4) evaluating the OPO performances in terms of maximum power, efficiency, temperature dependence, and tenability, (5) fabricating wide aperture OPO devices optimized by the applications.					
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Introduction

There are strong needs for tunable IR wavelength laser systems that are physically compact and mechanically robust, and are easy to operate for the applications in medical therapy, diagnosis, spectroscopy study, environmental sensing, and so on. Current IR laser systems that are utilized are not fully optimized for specific needs. Rather, what is used are existing laser systems that require modification, either during production or by the individual user. Essentially, no optimization of the wavelength for specific applications is made in existing systems. In addition, the size of these systems tends to be excessively large, operation tends to be overly sensitive to environmental conditions, and routine maintenance is still required.

Development of coherent terahertz radiation sources has also very wide applications from the biomedical imaging to the inspection of semiconductor devices^{1,2}) and spectroscopy study. However, in the conventional methods, there are some serious limits in the speed of photoconduction of the materials and by the dispersion and attenuation in the crystal. These limits are prohibiting the efficiency of light radiation.

In this program, we proposed to use Mg-doped stoichiometric lithium tantalate (SLT) originally developed in National Institute of Material Science (NIMS) for developing wide aperture frequency conversion devices based on their periodically poled structures. This enables to realize highly efficient, compact and robust IR and terahertz light sources. By this development, innovative applications will be also expected besides conventional possible applications in medical therapy, diagnosis, environment sensing and security.

In this proposal, we aimed at optimizing IR frequency conversion devices for particular applications, and solve remained issues in materials, for example, optical absorption in IR and THz wavelength regions. Moreover, we will design new devices for efficient generation of Terahertz light using Mg-doped SLT crystal.

According to the background above, we performed the program setting two titles of thrusts as below.

Thrust 1: Optimization of OPO system for IR light generation

Thrust 2: Efficient and tunable terahertz generation using QPM device

Here we report the results of two Thrusts separately.

Results of Thrust 1: Optimization of OPO system for IR light generation

In Thrust 1, we proposed to develop a tunable IR wavelength conversion device using quasi-phase-matched (QPM) optical parametric generation. Although the IR light source can be applied for various fields, here we specifically targeted our research toward dental surgical applications for the removal of hard enamel, dentine and bone tissues, at the same time developing a new capability for use in other tunable IR laser research and applications to interfacial media and biological sciences.

The project goals consisted of: (1) setting up the polarization switching system to fabricate QPM devices, (2) assembling the Mg:SLT based QPM devices, (3) setting up a new experimental capability

to generate tunable light around $2.78\mu\text{m}$ by the OPO system, (4) evaluating the OPO performances in terms of maximum power, efficiency, temperature dependence, and tenability, (5) fabricating wide aperture OPO devices optimized by the applications. Besides, we tried to solve the remained issues in materials, that is, optical absorption in IR wavelength region which often takes place and suppresses the efficiency in IR frequency conversion.

<Experiments and results>

We have assembled, developed, and utilized a QPM-OPO IR laser system.

Figure 1 displays a schematic of the setup.

In main, it consists of a low dispersion

Continuum Surelite Nd:YAG laser together

with an OPO laser cavity (QPM device oven

bordered by two IR coated flat coupling mirrors).

The Nd:YAG laser operates at the fundamental wavelength of 1064 nm to pump the QPM device. The 1064 nm beam is attenuated, and its polarization adjusted for maximum phase-matching. Further, the beam may be spatial filtered to enhance its Gaussian profile to aid conversion efficiency and limit potential laser damage.

A small, portable heating unit/temperature controller is used to tune the crystal locally (Figure 2, the white Teflon structure with black cooling fin). Under optimal laser beam alignment conditions, we have observed that tuning criteria can be met at a lower limit $115\text{ }^{\circ}\text{C}$. This relatively low temperature requirement is easily accommodated by the oven enclosure and poses little obstacle to the IR conversion.

We fabricated $2\times 2\times 35\text{ mm}^3$ periodically poled device with a QPM period of $31.7\text{ }\mu\text{m}$ using Mg-doped SLT crystal. Figure 3 shows the first light from the QPM-based OPO device. The visible red light is created by the mixing of the signal and pump laser beams in the QPM device ($\lambda = 657\text{ nm}$). It is a brilliant indication that phase matching is successful and IR light is being generated. The 532 nm green light is parasitic and is a consequence of the doubling of the pump 1064 nm pump beam entering the QPM

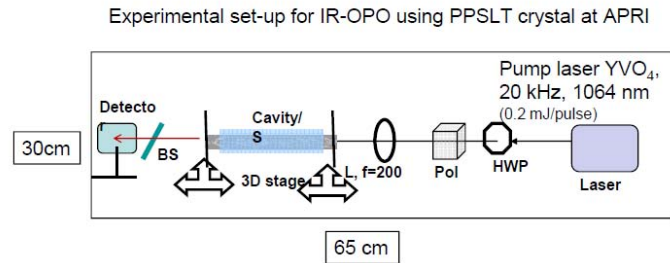
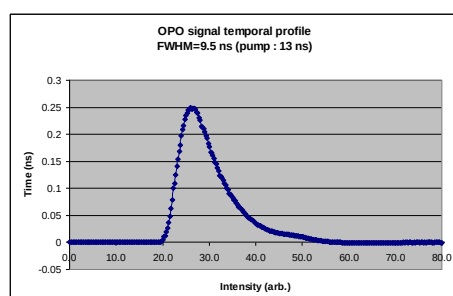


Figure 1: Schematic of the QPM-OPO IR conversion

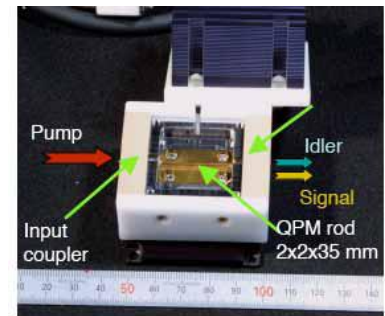


Fig.2: OPO module for controlling operation temperature.



Figure 3: First light from the QPM-based OPO device. Parasitic red and green lights can be observed.

device.

As displayed in Figure 3, IR conversion is successful and has elicited a total output power of 0.04W (2mJ/pulse). The

Figure 4: The measure temporal profile of the OPO output is slightly narrower than the 1064 nm pump.

measured temporal laser pulse of 9.5 nanoseconds (Figure 4) is slightly narrower than the pump width of 13 nanoseconds. This represents a peak output power of ~147 KW. Broad tunability has also been demonstrated as shown by Fig.5.

<Summary of Thrust 1>

Optimization of appropriate laser wavelengths for soft- and hard-tissue oral and maxillofacial removal applications has yet to be made in existing light sources. We have begun to address this specific problem using our newly developed tunable IR wavelength conversion

device utilizing quasi-phase-matching (QPM) optical parametric generation. QPM is a technique where the generated laser light is collinear to the pump laser; there is no laser beam walk-off as wavelength is adjusted. Optimal wavelength for soft- and hard-tissue evisceration can be achieved with one system and in real time without optical or mechanical adjustments. The largest nonlinear coefficient can be utilized for phase matching at any wavelength within the transparent range of the SLT crystal. We have successfully demonstrated that such a QPM device based on small, stoichiometric lithium tantalite (SLT) single crystals can be used in this alternative laser surgery system with easily controlled temperature-tuning for multi-tissue ablation.

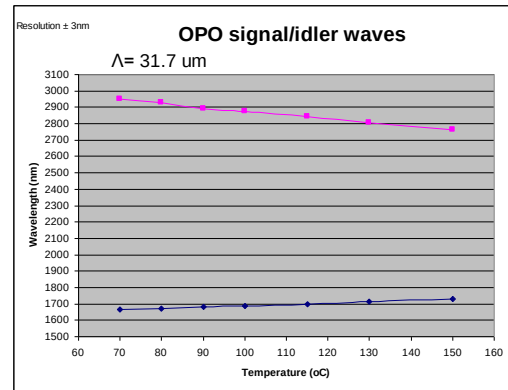


Fig.5: OPO signal (blue) and idler (pink) waves as a function of operation temperature.

Results of Thrust 2: Efficient and tunable terahertz generation using QPM device

Here we report on experimental demonstration of fine tuning of the narrow-band THz generation depending on fanned-out quasi-phase matched structure inSg-doped SLT, where we investigate THz absorption of the material (as shown by Fig.6) and tunability of the generation frequency.

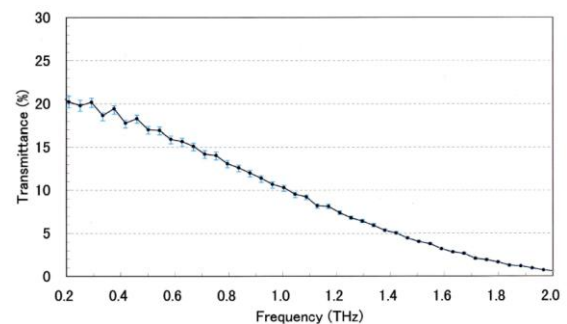
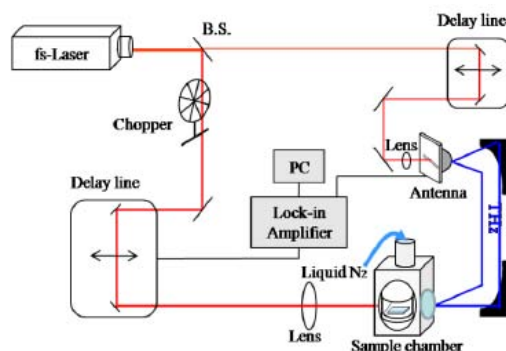


Fig.6: Measured Absorption of Mg-doped SLT as a function of THz frequency.

<Experimental set-up and results>

A Ti:sapphire oscillator system with repetition rate of 76 MHz and pulse duration of 190 fs was used as the fs laser



source at the center wavelength of 790 nm. The incident fs laser beam was divided into two as pump and probe beams, respectively, for THz generation and

Fig.7: Experimental setup for THz generation at low temperature and detection in time-domain measurement

detection. The optical power of pump beam was 450 mW and it was focused to the sample with the beam size of roughly 150 μm in diameter using a lens. The pump beam was chopped at 2 kHz and detected by a lock-in amplifier as shown in Fig. 7. The sample was cooled in a mini-cryogenic chamber which has two optical windows. The front and the rear windows were made of optical quartz for the transmission of the fs optical beam and TPX (4-methyl- penten-1) for the THz transmission, respectively, and their size was 2 inches in diameter. Liquid nitrogen was used for the system cooling. The generated output THz wave was collected and focused by two off-axis parabolic metal mirrors. For the THz detection, a low temperature grown GaAs photoconductive antenna with a dipole gap of 5 μm was used and a hyper-hemispherical Si-lens was attached on the antenna to focus the THz beam to the gap. As a reference, LiTaO₃ crystal was used to investigate THz generation in normal dispersive material without QPM structure. And 2-mm long PPSLT sample with different grating period of 60 and 30 μm , respectively, were used to explore the difference of THz generation depending on material and QPM periodicity.

The fact that THz radiation was generated only around the surface of the LiTaO₃ with THz absorption due to the large dispersion incited us to apply both QPM structure and low temperature operation to enhance the THz generation further. The main idea is to utilize material dispersion actively. If the periodically poled domain length is comparable to the walk-off length, each domain will contribute to the THz radiation independently. Because of the alternating sign of the nonlinearity at each domain, the generated THz waves have alternating waveforms. Then the THz field will not cancelled out even inside of the bulk crystal. As the result, the period of one cycle of the THz waveform will correspond to the length of a domain in QPM structure. And the bandwidth of the integrated THz pulse from the poled domains will be inversely proportional to the number of them.

In the experiment, THz generation and detection was performed as a function of temperature. The generated multi-cycles of THz pulses in time-domain measurement using the 2 mm-long PPSLT crystal with QPM period of 60 μm are presented in Fig. 8 (a). The number of THz cycles in waveform is $N/2$, where N is the total number of the domain (here $N = 66$). At low temperature ($T=133\text{ K}$), the measured THz waveform consists of 33 cycles with relatively same amplitude. It agrees well with the total number of the periodic poled domains. On the other hand, at room temperature ($T= 300\text{ K}$),

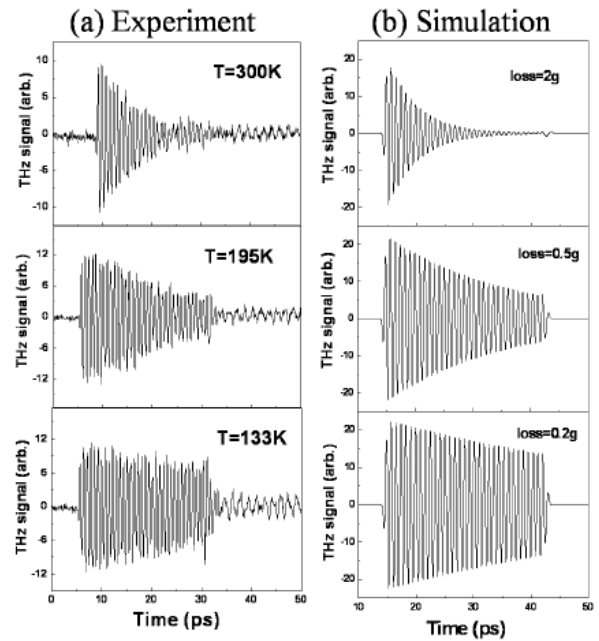


Fig. 8: Measured and simulated THz waveforms at PPSLT crystal. Simulation parameters are used as $L= 2.0\text{ mm}$, $t= 190\text{ fs}$, and QPM period of 60 μm . The loss parameter of THz wave, $g=7.5 \times 10^{-3}\text{ THz}^{-1}$ is

strong decay of the waveform was observed due to the linear THz absorption in the crystal.

<Summary of Thrust 2>

Tunable narrow-band THz generation was demonstrated using an fs laser in QPM structure. Simultaneously generated forward and backward THz waves were clarified by DFG process within the spectral bandwidth of the pump laser. The generations of 1.38 and 0.65 THz with narrow bandwidths of 32 and 23 GHz, respectively, will enable us to use this as a significant coherent light at THz range. At room temperature, THz signal was decayed exponentially along the crystal length due to the THz absorption by transverse optical phonons. To reduce the THz absorption, we employed cryogenic cooling on samples using liquid nitrogen. In PPSLT sample, we obtained almost nine times higher power at $T=133\text{K}$ than at $T=300\text{K}$.

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