External Cavity Diamond Raman Laser at 2.52 μm

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Abstract: An external-cavity diamond Raman laser at 2.52 μm, pumped by a home-built Tm:YLF laser, is reported. The maximum output pulse energy is 1.1 mJ for 4.74 mJ incidence yielding a total conversion efficiency of 23%.The slope efficiency is 49% and the Raman pulse duration is between 23-26 ns for 42 ns pump pulse duration.
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1. Introduction

Laser sources operating in the mid-infrared (IR) are of interest for a wide range of applications including sensing, free space communications and clear plastics welding and processing. However mid-IR laser technology has not fully matured yet relying only on a limited range of materials, therefore creating the need for the development of new materials providing either direct laser generation or wavelength conversion of already existing sources for accessing this important wavelength region.

Stimulated Raman scattering which has been demonstrated in solid-state materials as early as 1963 [1], has been successfully utilized during the past decades for generating longer wavelengths from relatively mature laser sources [2]. Raman conversion in the mid-IR and beyond, however, is challenging due to reduced Raman gain and limited range of transparent Raman materials. Diamond is a promising material for overcoming these challenges as it presents higher Raman gain coefficient than most crystals [3], it has unrivalled thermal conductivity [4], and high damage threshold, which make it an excellent candidate for high power applications. This crystal also has very broad transmission range extending from ultraviolet to THz. There is however a drop in diamond transmittance in IR between ~2.5 and ~6.5 μm caused by multi-phonon absorption. Previously Raman oscillation in 3.38-3.8 μm spectral region in diamond was demonstrated with 15% conversion efficiency limited by this absorption feature [5].

In this work we utilize a distinct advantage of diamond for Raman applications, namely its high Raman frequency (1332 cm^{-1}, which is notably larger than that in other Raman crystals (<1100 cm^{-1}) [3]) enabling a first Stokes wavelength at ~2.55 μm when the already mature technology of Thulium lasers (~1.9 μm) is used as pump. 2.55 μm is at the edge of the multi-phonon absorption feature in diamond and feasibility of Raman oscillating in this spectral region with high conversion efficiency was tested. Also, this specific wavelength is of particular interest for clear plastics welding applications as a big range of clear (transparent in visible) plastics used in medical and aerospace applications present a significant rise in their absorption at wavelengths longer than ~2.5 μm.

2. Raman laser, experimental results and discussion

The pump laser for the diamond Raman laser (DRL) consisted of a 24 mm long 2 at.% Tm:YLF crystal (with no anti-reflection (AR) coatings) placed in a 145 mm long laser cavity. The Tm:YLF was pumped by a 792 nm diode laser and q-switched using a water cooled acousto-optic modulator. The output wavelength was not fixed and so drifted between 1886 and 1891 nm predominantly due to temperature fluctuations in the lab. The maximum output pulse energy was 5 mJ with 0.119 MW of peak power. The pulse repetition rate was 5 Hz and the pulse width, measured with an InGaAs detector (Thorlabs PDA10D-EC), was ~42 ns. The limiting factor for the output pulse energy of the Tm:YLF laser was the damage threshold of the Tm:YLF crystal (15 J/cm^2).

The Tm:YLF laser was used to pump a DRL at 2.52 μm. The DRL consisted of two Brewster-cut diamonds with lengths of 4- and 5.6 mm respectively, yielding a total length of 9.6 mm, placed in a 12.5 mm long cavity. The diamonds had low-nitrogen content, ultra-low birefringence and were grown via chemical vapor deposition by Element 6 UK. The *P*-polarized pump beam was parallel to a <110> axis of the crystals. A curved mirror with 50 mm radius of curvature, highly transmissive for ~1.9 μm and highly-reflective coated for ~2.55 μm was used as input coupler, whereas a flat mirror with 80% reflectivity at both pump and Raman wavelengths was used as output coupler. The output of the Tm:YLF laser was focused in the DRL cavity using two different CaF_2 lenses, both AR-coated for 1.9 μm, with focal lengths of 75- and 100 mm yielding beam radii at the focus of 52.5- and 70 μm respectively. The corresponding Rayleigh lengths were ~4 mm for the 75 mm lens and ~7 mm for the 100 mm lens.

The energy transfer characteristics of the DRL for the case of the 75 mm CaF_2 lens are presented in figure 1(a). The threshold was at about ~3.5 mJ incident pulse energy and the slope efficiency was 49%. The maximum output pulse energy was 1.1 mJ for 4.74 mJ incident, yielding a total conversion efficiency of 23%. The pulse width of the

DRL was measured with a Thorlabs PDA10D-EC detector and was always found between 23-26 ns. Although the threshold was expected to be higher in the case of the 100 mm CaF_2 lens due to the bigger waist radius at focus, in practice it was found to be about the same as the case of the 75 mm CaF_2 lens (~ 3.5 mJ). This is attributed to the shorter Rayleigh length of the 75 mm CaF_2 lens (~4 mm) comparing to the Rayleigh length of the 100 mm CaF_2 lens (~7mm) and the total length of the diamonds (9.6 mm).

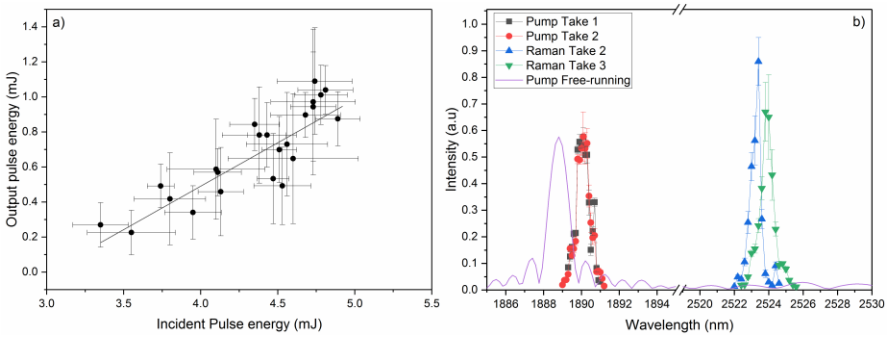

Figure 1. a) Energy transfer (with corresponding standard deviations of the pump and Raman pulse energies) of DRL for the 75 mm focal length CaF_2 lens; b) Spectra of pump and Raman wavelengths acquired with a monochromator (points) and spectrum of the pump in free running mode (solid line) acquired with an optical spectrum analyser.

The collected spectra for both the Tm:YLF pump and DRL are presented in figure 1(b). These were acquired using a Spectral Products CM110 monochromator and a Thorlabs PDA10D-EC detector. A spectrum of the Tm:YLF pump in free-running regime collected with an optical spectrum analyzer (Thorlabs OSA205) is included as well. The drifting of the pump spectrum which was mentioned above and which subsequently causes the same effect in the generated Raman wavelengths (Raman takes 2 and 3 if Fig. 1(b)) is evident in this figure. The FWHM width of the spectra for both the Tm:YLF pump and DRL was measured to be ~1 nm although this measurement is possibly affected by the wavelength drift and instabilities of the lasers.

It is worth noting that the quite large error bars of figure 1(a) indicate a fluctuating and unstable operation of both the pump and the DRL. This instability is attributed to a combination of factors: atmospheric absorption which is present at both the pump and Raman wavelengths; DRL oscillation too close to the Raman threshold; the fact that the Raman gain in diamond is wavelength dependent [6] and any wavelength instabilities in the Tm:YLF pump, translate in output power instabilities in the DRL. The absorption coefficient of diamond at 2.52 μm was measured with FTIR spectrometer (Cary 630) to be 0.11 cm^{-1}. This yields 20% round-trip losses for our diamonds (total length of 9.6 mm). These high intrinsic losses limit conversion efficiency of the DRL. We believe shifting of the pump emission towards shorter wavelength (e.g. 1875 nm) should significantly improve the performance of the DRL while still keeping the first Stokes wavelength in the industrially-important spectral region of ~2.5 μm.

3. Conclusions

In conclusion we have reported the operation of a DRL at 2.52 μm when pumped by a q-switched Tm:YLF laser at ~ 1.89 μm. The maximum output pulse energy of the DRL was 1.1 mJ for 4.74 mJ incidence which yielded a total conversion efficiency of 23%. To the best of our knowledge this is the first report on a mid-IR DRL at ~ 2.5 μm pumped by a Thulium laser. This work paves the way for accessing a new range of wavelengths in mid-IR which are of great interest for sensing and materials processing applications.

4. References

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