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5.9 GHz graphene based q-switched modelocked mid-infrared monolithic waveguide laser

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Abstract: A high repetition rate Q-switched modelocked ~2.1 µm monolithic waveguide laser is reported. Ultrafast laser inscription is used to fabricate 3D depressed cladding channel waveguides in holmium doped yttrium aluminium garnet. This results in a transversely single mode waveguide laser. With the use of a graphene based saturable output coupler, Q-switched modelocking was achieved with a pulse repetition frequency of 5.9 GHz and up to 170 mW of average output power. This first demonstration of multi-GHz repetition rate operation from a Ho3+:YAG laser provides a compact and convenient source for a number of applications.

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1. Introduction

In recent years there has been considerable growth in the interest of pulsed lasers in the 2 µm spectral range. This is due to a great many potential applications including for example: medical [1] and material processing [2]. This wavelength range lies within a window of atmospheric transmission which overlaps with the characteristic absorption lines of a number of gas molecules. As a result sources in this region find use in sensing and environmental monitoring [3]. In addition, wavelengths around 2 µm have high absorption in water molecules which are vastly present in the human body making them attractive for medical and biological use [4,5]. Many applications however require short pulse duration and high pulse repetition frequency (PRF) i.e. multi GHz; these include high speed optical communication as well as optical frequency combs for precision metrology. GHz range PRFs are required to obtain the high level of precision and resolution required for these types of applications [6–8] and therefore justify the need to develop high repetition rate pulsed sources in this spectral range.

The generation of ultrashort pulses in the mid-IR is often achieved by passively modelocking a solid state bulk [9] or doped fibre laser [10] with a suitable choice of saturable absorber (SA). One of the most commonly used SA’s are semiconductor saturable absorber mirrors. However, these have complex fabrication procedures and the cavities tend to be inherently long therefore restricting the maximum PRF to the MHz range. Other saturable absorbers include black phosphorus and diselenide based materials which have been shown to be effective in ultrashort pulse generation [11] and q-switching [12,13] respectively. Another method which is commonly used for mid-IR pulse generation is that of a modelocked solid-state laser combined with an Optical Parametric Oscillator for widely tunable pulsed operation [14,15]. These setups require a number of free space optics resulting in complex and relatively large system which can often lead to issues with sensitivity to the surrounding environment and deem them unsuitable for some applications. As a result there remains a real need to develop compact and robust systems which not only overcome the challenges discussed associated with alternate methods but also have the ability to generate ultrashort high PRF pulses in the mid-infrared.

A commonly used and widely available gain medium which emits in the ~2 µm spectral range is Ho3+ doped YAG. It is commonly in-band pumped at 1.9 µm resulting in a quasi-3 level system emitting at 2.1 µm [16]. The type of pump sources required at 1.9 µm are readily available with high power capabilities and good beam quality in the form of Tm:fibre lasers [17–19] and as a result Ho3+:YAG has become a well-researched and established laser gain medium. In spite of becoming a widely available laser material there have been few demonstrations of singly doped Ho3+:YAG modelocked lasers with short picosecond pulse widths [17, 19, 20] and none to date with a high PRF in the multi GHz range. The shortest pulse width demonstrated from this material until very recently was 2.1 ps, the laser operates with a PRF of 82 MHz [21]. However, the first fs Ho3+:YAG oscillator has now been demonstrated with an impressive pulse width of 220 fs [22]. Here we demonstrate a Q-switched modelocked (QML) regime in which the laser outputs passively modelocked short pulses under the envelope of a Q-Switch [23]. In spite of the Q-switching behavior there is potential for a vast amount energy to be stored within in the Q-switch, in effect the output has much higher peak pulse energy than that of continuous wave modelocked lasers. Although in many cases the presence of QML is undesirable, the advantage of QML lies in its use as a source for subsequent amplification. The delay between groups of pulses emitted during QML can allow appreciable energy storage in amplifiers, leading to very high power pulse generation. Conversely, pure CW mode locking often requires “pulse pickers” to isolate
single pulses or groups of pulses in order to realize appreciable energy gain in later amplifier stages.

Graphene has attracted much attention as a saturable absorber (SA) in the development of ultrafast pulsed laser sources. This is because this material has intrinsic broadband operation, low saturation fluence and ultrafast recovery time [24]. In addition to these parameters, a single layer/multiple layers of graphene can be coated with some ease onto a standard reflective output coupler resulting in a Graphene coated Saturable Output Coupler (GSOC) which can be a useful alternative to more common SA’s such as Semiconductor Saturable Absorber Mirrors (SESAMs) which have complex fabrication procedures [25]. A short laser cavity length is inherent to the production of a high PRF as the PRF itself is inversely proportional to cavity length. Employing a waveguide geometry provides an elegant solution to achieve GHz PRFs. This is because tight confinement in the waveguide ensures good overlap between the pump and signal beams resulting in low lasing thresholds and high gain over short material lengths [26–28]. The cavity mirrors can be aligned directly at the end facets of the waveguide resulting in cavity lengths as short as a few mm. Furthermore a GSOC can be easily incorporated into a waveguide laser cavity.

Ultrafast Laser inscription (ULI) is an effective and relatively simple technique for the fabrication of buried 3D waveguide structures in crystal and glass substrates. The basis of ULI is to tightly focus femtosecond pulses beneath the surface of a substrate which is transparent to the inscription laser wavelength. This induces localized permanent changes in the material properties at the focus by means of nonlinear absorption processes. Type I waveguides are the result of inscribing a region of increased refractive index in the material; the light is therefore confined to the modified area of the material. Type II waveguides are formed by inscribing two parallel regions in which the material refractive index is reduced, these are called damage lines and propagating light is confined in the unmodified material between the damage lines [29]. However, a third type of waveguide, called depressed cladding structures, are found to often be favorable over the other types for the confinement of mid-IR light in crystalline structures. These waveguides were first demonstrated by Okhirmchuk et al. in Nd:YAG and are formed by inscribing a series of reduced refractive index elements in a circular fashion constructing the cladding of a waveguide, light is in effect confined to the unmodified region in the centre of the inscribed elements [30].

There have been previous reports of many waveguide lasers with GHz PRFs in the ~1-2 µm spectral range which have been passively CW modelocked with SESAMs [31,32]. Graphene has also been used many times as a saturable absorber whilst incorporated with a waveguide geometry and has proven useful for producing all regimes of pulse generation; Q-switched at 1 µm [33], QML at 1 µm [34], 1.5 µm [35] and ~2 µm [36] and also pure CW modelocking at an impressive 11 GHz PRF [37]. QML has also been reported from a 2 µm waveguide laser using a bismuth telluride based SA [38]. In this work ULI was used to fabricate a highly compact Ho³⁺:YAG depressed cladding waveguide laser which operates at 2.1 µm and is Q-switched modelocked using a Graphene SA. The modelocked pulses are output with a PRF of 5.9 GHz under a Q-switched envelope which has a rep. rate of ~1 MHz. A maximum average output power of 170 mW was demonstrated.

2. Fabrication of the graphene coated saturable output coupler

Graphene was coated onto a standard output coupler which is 80% reflective in the wavelength range 1.7-2.7 µm, this results in a double pass of pump signal as 80% of it is reflected back into the cavity. The deposition of the graphene was carried out via transfer from commercially available graphene coated copper foil. The graphene-Cu foil was also coated with a layer of PMMA; this is to prevent any graphene being removed in error during the process. The copper itself was dissolved in diluted ferric chloride and then the graphene/plastic was placed on to the mirror surface after being rinsed with methanol and water. Finally the plastic was dissolved with acetone. This resulted in the mirror being coated
with multiple layers of graphene; typically less than 10 layers at any place on the surface. A detailed description of the process used to produce the GSOC is given in [39]. The nonlinear transmission of the GSOC has been measured with an optical parametric amplifier operating at 2.1 µm which generated 100 fs pulses with a PRF of 1 kHz. The GSOC was placed in the path of the incident beam and the nonlinear transmission was calculated through the measurement of the output power as a function of the input pulse fluence. The result is shown in Fig. 1. From this result it is apparent that the GSOC has a modulation depth of ~6.6% and the nonsaturable loss is 80.3%. The GSOC has a measured saturation fluence of ~8.6 µJ/cm² which is comparable to commercially available SESAMs in this wavelength region which tend to have a maximum saturation fluence of 10s of uJ/cm² [40]. (BATOP SAM λ = 2000 nm range).

![Graph showing nonlinear transmission versus pulse fluence at 2.1 µm for GSOC.](image)

**Fig. 1.** Nonlinear transmission versus pulse fluence at 2.1 µm for GSOC.

### 3. Waveguide laser fabrication and results

The inscription laser used for the waveguide fabrication was a modelocked, chirped pulse, amplified Yb:fibre laser (IMRA µJewel D400) which operated with a pulse rep. rate of 500 kHz, pulse duration of ~360 fs and central wavelength 1043 nm. The Ho³⁺ : YAG substrate was doped with 0.5% holmium and had dimensions of 5x5x14 mm³. The particular waveguide which was used to obtain QML operation was inscribed in the long length of the substrate. It was inscribed by focusing the laser using a 0.4 NA lens at a distance of 250 µm below the substrate surface. 60 elements were subsequently inscribed at a translation speed of 10 mm/s and average laser output power of 125 mW. This resulted in a depressed cladding waveguide with diameter 50 µm which exhibited transverse single mode output at the waveguide laser wavelength of ~2.1 µm. A full CW laser characterization and description of this waveguide is given in [41] and image of the end facet is shown in Fig. 2.

![Image of end facet of depressed cladding waveguide structure inscribed in Ho³⁺:YAG substrate.](image)

**Fig. 2.** End facet of depressed cladding waveguide structure inscribed in Ho³⁺:YAG substrate.

The pump source used is a CW Tm:fibre laser with emission wavelength = 1908 nm a maximum output power of 12 W (TLR-20-1908-LP). A polarizing beam splitter and quarter
A waveplate arrangement is used before the pump beam is input into the laser cavity, this is to prevent feedback into the pump laser from Fresnel reflections of the Ho:YAG sample surface. This used alongside a half wave plate results in a circularly polarized input pump beam and also allows for fine control of the pump power.

Figure 3 is a schematic of the laser cavity. L1 and L2 are both lenses which are anti-reflective (AR) coated from 1.65 to 3 µm and have focal lengths of 40 mm and 50 mm respectively. M1 was AR coated on the rear side for 1.7-2 µm so allowed the maximum coupling of pump light into the waveguides and HR for 2.05-2.43 µm on the front side facing the Ho³⁺:YAG sample. The GSOC was positioned very close to the output facet of the sample but avoiding contact with it, this is to minimize the cavity length but protect the graphene from damage. LP 2000 is a long pass filter for 2000 nm to filter out any pump power before measuring the laser output.

Precise alignment of the laser cavity and in particular the incoupling mirror M1 and the GSOC produced pulsed operation of the Ho³⁺:YAG waveguide laser. The QML results for this GSOC are shown in Fig. 4.

The laser spectral output is shown in Fig. 4(a) and was measured with a Thorlabs Optical Spectrum Analyzer (OSA 205) with a resolution of 0.01 nm. The spectrum is centered at approximately 2091 nm and has a full width at half maximum bandwidth of ~0.8 nm. Figure 4(b) plots the average output power against the pump power. As can be seen by the linear fit in this graph the QML laser slope efficiency is 6.8% and at the highest incident pump power of 2.5 W, the average power emitted was 170 mW. At a pump power of 2.7 W damage to the Graphene was observed and as a result the damage threshold is estimated to be 1.6 µJ/cm², the maximum pump power was therefore restricted to 2.5 W to ensure the Graphene could not be damaged. There is a decrease in slope efficiency of around 3% when compared to the CW operation of this waveguide reported in [41]. This is most likely due to the extra loss incurred because of the gap between the GSOC and the waveguide output facet, it was found during CW investigations that the single mode WG produced the highest slope efficiencies when the cavity mirrors were as close to the sample as possible as this resulted in optimum alignment. There was no region of only Q-switching observed as the laser was found to be QML on the onset of threshold; likely due to the saturation characteristics of the GSOC. The laser was only pumped with a maximum of 2.5 W to protect the GSOC from damage as pump powers above this were seen to ablate the graphene layer.
Fig. 4. (a) QML Ho\textsuperscript{3+}:YAG waveguide laser spectral output, (b) output power versus incident pump power, (c) RF Spectrum; the graph has a span of 150 MHz and was taken with a resolution bandwidth of 1 kHz, (d) q-switched pulse train, (e) modelocked pulse train.

The output RF spectrum is shown in Fig. 4(c), it was measured using a high speed 12.5 GHz InGaAs photodetector (Newport 818-BB-50) connected to a 13 GHz RF spectrum analyzer (Agilent E4405B ESA-E). From this it can be seen that there are pulses being emitted from the Ho\textsuperscript{3+}:YAG laser with a PRF of about 5.860-5.865 GHz. As a number of peaks can be seen in the RF spectrum as opposed to 1 single narrow peak this is the first implication that the laser is in the QML regime rather than the Continuous Wave modelocked regime. The graph in Fig. 4(d) presents the Q-switched envelope on a microsecond scale (2 µs/division). The repetition rate of the Q-switch is ~1.04 MHz resulting in a pulse energy of 0.16 µJ associated with each Q-Switch pulse. The train of modelocked pulses emitted under the Q-switch are shown in Fig. 4(e) on a scale of 0.1 ns per division and this corresponds to the peak on the RF spectrum in Fig. 4(c). The pulse trains of both the modelocked and Q-switched pulses have been recorded with the high speed photodetector described above and a
23 GHz Tektronix MSO/DPO72304DX oscilloscope. One can estimate the fundamental repetition frequency of a Fabry-Perot cavity using:

\[ f_{\text{rep}} = \frac{c}{2nl} \]  

In Eq. (1) \( c \) [\( \text{ms}^{-1} \)] is the speed of light, \( n \) is the refractive index of the waveguide and \( l \) is the cavity length [42]. The cavity used here has length of approximately 14 mm and using this in Eq. (1) gives an estimation for the PRF of 5.9 GHz. This is in good agreement with the experimental results shown in Fig. 4. (c) where spikes in the RF spectrum are observed from 5.860 to 5.865 GHz. The emission of both the pulses and Q-switch was found to be particularly stable at low powers for several hours, but if operated at high pump power > 2 W the laser became unstable with rapidly changing peak power occurring or cease to pulse at all. This is a result of both thermal issues due to heat building up inside the cavity and possible damage to the Graphene itself.

The QML regime behavior observed from the laser can be verified using a stability criterion which gives an estimation of the intracavity pulse energy required to escape the Q-switching instabilities. The critical pulse energy \( E_{P,c} \) is calculated using Eq. (2) and is defined as the minimum pulse energy required from the laser to establish stable CW modelocking and therefore for pulse energies below this value, the laser will exhibit this QML behaviour.

\[ E_{P,c} = \left( E_{\text{sat,L}} E_{\text{sat,A}} \Delta R \right)^{1/2} \]  

In Eq. (2) \( E_{\text{sat,L}} \) is the saturation energy of the laser gain material which is the product of the material saturation fluence and effective laser mode area inside the gain medium, \( E_{\text{sat,A}} \) is the saturation energy of the absorber which is the GSOC in this case, and similarly is the product of the saturation fluence of the GSOC film and the effective laser mode area incident on it. Finally, \( \Delta R \) is the maximum modulation depth of the GSOC [23]. Using these parameters a value of \( E_{P,c} = 2.6 \times 10^{-8} \) J is calculated and is found to be 3 orders of magnitude greater than the maximum intracavity pulse energy \( E_p \) emitted by the Ho\(^{3+}\):YAG waveguide laser which is calculated to be \( 2.9 \times 10^{-11} \) J, this is in agreement with the experimental results as the laser output is well within the QML instabilities limit. In an attempt to overcome the CW mode-locking threshold the GSOC should have a higher reflectivity value as well as a reduced modulation depth. In addition a lower loss waveguide would lead to an increase the slope efficiency ensuring no loss of output power. To summarize, with careful tailoring of the ULI parameters the laser efficiency and therefore output power could be significantly improved, this as well as the careful design of the GSOC parameters, means the cavity could be optimized to operate in the stable CW modelocked regime while retaining the high PRF of the output.

4. Conclusion

We have demonstrated a passively Q-switched Modelocked Ho\(^{3+}\):YAG laser at 2.091 µm. The waveguide was fabricated using Ultrafast Laser Inscription and a thin film of graphene was coated on to a reflective output coupler to form a saturable absorber. With both of these features integrated into the cavity a short cavity length was obtained resulting in a high PRF of 5.9 GHz. This result is a promising for the development of robust, compact and practical mid-infrared pulsed laser sources.

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