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Broadly tunable mode-locked Ho:YAG ceramic laser around 2.1 μm

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Abstract: A passively mode-locked Ho:YAG ceramic laser around 2.1 μm is demonstrated using GaSb-based near-surface SESAM as saturable absorber. Stable and self-starting mode-locked operation is realized in the entire tuning range from 2059 to 2121 nm. The oscillator operated at 82 MHz with a maximum output power of 230 mW at 2121 nm. The shortest pulses with duration of 2.1 ps were achieved at 2064 nm. We also present spectroscopic properties of Ho:YAG ceramics at room temperature.

OCIS codes: (140.4050) Mode-locked lasers; (140.3070) Infrared and far-infrared lasers; (160.3380) Laser materials.

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1. Introduction

Ultrafast lasers in the wavelength range around 2 μm provide great potential for applications like LIDAR, remote sensing, optical communication, and can be used as pump and seed sources in optical parametric amplifiers operating in the mid-IR [1–5]. Holmium ion (Ho^{3+}) doped materials are attractive for building ultrashort pulse laser sources slightly above 2 μm due to the broadband emission related to the $^5I_7 \rightarrow {}^5I_8$ transition. In principle, diode-pumping of such lasers can be achieved by co-doping of the active material with thulium ions benefiting from common 800 nm laser diodes and the energy transfer to Ho^{3+} ions [6]. Such energy transfer, however, eventually limits the overall pump efficiency while up-conversion mechanisms leads to excitation of higher energy levels of Tm^{3+} whose population is no longer integrated in the transfer of energy to Ho^{3+}. Thus, direct excitation of the Ho upper emitting level using a laser pump source remains the most promising approach for up-scaling the output power and increasing the efficiency of all-solid-state singly Ho-doped lasers emitting on the $^5I_7 \rightarrow {}^5I_8$ transition. This scheme, also known as in-band pumping or resonant pumping, ensures minimum thermal load which is essential for quasi-three level operation in order to avoid re-absorption. Although an in-band diode-pumped Ho:YAG laser has been reported with 1.9 μm laser diodes [7], efficient and powerful diode-pumped Tm-doped lasers are widely used for pumping singly Ho-doped lasers [4], including mode-locked lasers [8].

YAG ($Y_3Al_5O_{12}$) with its outstanding thermo-mechanical properties is one of the most studied Ho-ion hosts and exhibits notable features, e.g. in terms of thermal conductivity and operation in a broad temperature range (−40°C - + 40°C) [4]. Since Ho-doped media emitting on the $^5I_7 \rightarrow {}^5I_8$ transition are quasi-3-level lasers, operation at low or cryogenic temperatures would increase the laser efficiency compared to operation at room temperature. However, only little attention has been paid to mode-lock Ho:YAG lasers yet. Using Cr,Tm,Ho-codoped YAG pumped by a Kr-ion laser, 800 ps pulses were produced by active (acousto-optic) mode-locking [9]. Passive mode-locking of a Ti:sapphire laser pumped Tm,Ho:YAG laser using a semiconductor saturable absorber (SESAM) [10] resulted in ~21 ps pulse duration [11]. Finally, the only reports on a singly Ho-doped YAG crystal deal with actively mode-locked lasers, delivering pulses with duration of 102 ps [12] and 241 ps [13].

Thus, despite more than two decades of efforts, mode-locked Ho:YAG lasers have only been demonstrated with pulse durations of a few 10 ps around 2.1 μm [11–13]. The above mentioned beneficial thermal properties of the crystalline host therefore come at the expense of a fairly limited mode-locking performance so far. As an alternative, YAG laser ceramics appear promising, combining beneficial thermal properties with potentially less restrictive bandwidth limitations than crystalline hosts.

Ceramics exhibit a number of advantages. The manufacturing of laser ceramic materials is generally simpler than single-crystal growth. Furthermore, larger dimensions, higher doping concentrations as well as simplified shaping and processing are achievable [14]. Unfortunately, only a limited number of materials, such as YAG, LuAG and some of the cubic sesquioxides, can currently be fabricated as ceramics.

After the successful laser demonstration of Nd- and Yb-doped ceramics, efforts have focused on the realization of high quality Ho-doped ceramics. In 2010, the sintering process for the fabrication of Ho:YAG transparent ceramics and the first laser operation were reported [15,16]. Subsequently, their diode-pumped continuous-wave (CW) laser performance was significantly improved, and output powers of more than 20 watts were obtained, with slope efficiencies exceeding 60% [17]. Tunability of Ho:YAG ceramics has been reported in the Q-switched laser regime [18]. First investigations of the Ho:YAG ceramics spectroscopic properties, including absorption and fluorescence, have been presented in [15].

A challenging issue for laser mode-locking around 2 μm is the selection of suitable saturable absorbers for this spectral range. At shorter wavelengths, GaAs- and InP-based SESAMs typically provide tens or hundreds of picoseconds relaxation time in the near-infrared. To accelerate their absorption recovery time diverse post-processing techniques [10,19] and surface quantum well designs [20] were developed. Near 2 µm, GaSb-based quantum well (QW) structures are utilized as saturable absorbers for mode-locking, mainly applied for active materials with Tm-doping or co-doping [11,21–27]. The properties of GaSb-based SESAMs exhibiting "classical" and near surface designs suggested a surprisingly fast absorption recovery time of a few picoseconds which is rather independent of growth temperature or strain in the QWs [28,29].

Broad spectral tuning ranges are expected for GaSb-based SESAMs because the gain (or absorption in the case of SESAMs) of GaSb-based QWs is very broad. By preparing GaSb DFB lasers with different grating periods, wavelength coverage from 1980 to 2040 nm was obtained from a single epitaxial structure design [30]. With a slightly different QW/barrier design an extremely wide optical gain between 2.2 and 2.5 µm has been demonstrated [31]. Furthermore, the very flat gain spectrum of this material should be advantageous for broadband mode-locking. This potential was first confirmed by a 95 nm tuning range from 1979 to 2074 nm using a Tm-doped gain medium [22].

Here we report a passively mode-locked Ho:YAG ceramic laser employing a near-surface GaSb-based SESAM, setting a new record pulse duration for this promising laser material. The transparent ceramic is in-band pumped and the mode-locked laser is tunable between 2059 and 2121 nm.

2. Ho:YAG ceramics and GaSb-based SESAMs

A 1 at.% Ho-doped YAG ceramic sample was prepared by the solid-state reaction and vacuum sintering method using high-purity powders of Y_2O_3, α-Al_2O_3 and Ho_2O_3 as starting materials [15]. The highly transparent active element was 4 mm long with an aperture of ~3 × 3 mm^2. The input and output faces were polished with optical quality and no coating was applied. The ceramic sample was wrapped with Indium foil for better thermal contact and mounted in a copper holder providing cooling from the four lateral faces.

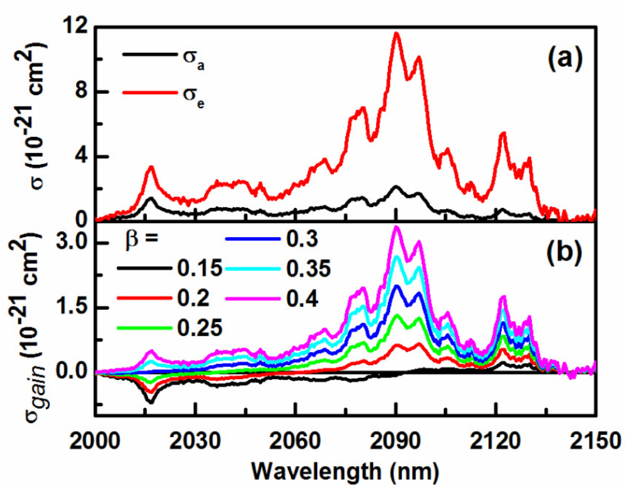

Fig. 1. Spectroscopic characterization of the 1% Ho-doped YAG ceramics in the 2-µm region. (a) Absorption σ_a and emission σ_e cross section. (b) Gain cross section σ_{gain} for different inversion levels β.

In order to estimate the potential spectral emission of the Ho:YAG ceramics, the gain cross section $\sigma_{gain} = \beta\sigma_e$ - $(1-\beta)\sigma_a$ for several values of the population inversion parameter β is calculated and presented in Fig. 1(b). The emission cross section σ_e was deduced from the absorption cross section σ_a (both shown in Fig. 1(a)) according to the McCumber theory. β is

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the ratio of the number of excited Ho^{3+}-ions in the $^5I_7$ manifold to the total Ho^{3+}-ion density. All the Ho:YAG ceramics cross sections are very similar to those of their single crystal counterpart [7]. The maximum emission cross section of the ceramic for the $^5I_7 \rightarrow {}^5I_8$ Ho^{3+} laser transition at 2090 nm is 1.16×10^{-20} cm^2. This value is only slightly smaller compared to Ho:YAG single crystals: $\sigma_e = 1.29 \times 10^{-20}$ cm^2 [7]. Comparing the gain cross sections for the 1 at.% Ho-doped YAG ceramics and the single crystal, the wavelength dependence is somewhat smoother in the former case which is potentially advantageous for increasing the mode-locked pulse bandwidth. For inversion levels β <20% emission of the free running laser is expected at 2120 nm, whereas for higher β the maximum gain is at 2090 nm (Fig. 1(b)). The relaxation time of the $^5I_7$ emission for the 1 at.% Ho:YAG ceramics was measured as 8 ms at room temperature, which is in good agreement with the value reported for single crystals [32].

With respect to our recent studies on mode-locked lasers around 2 µm based on Tm-doped active materials, best results were achieved with GaSb-based SESAMs comprising a low number of QWs which are placed near the surface [25–27]. That also applies for the investigated Ho-doped mode-locked laser. The selected anti-resonant SESAM contained two QWs separated by a 10 nm GaSb barrier. In our near-surface SESAM design, the upper QW is separated from the surface by a cap layer having a thickness of 5 nm. A more detailed description of the used SESAM including a drawing can be found in [28]. In contrast to the mode-locked Tm-doped lasers [25–27], best performance was achieved without additional AR-coating of the SESAM. Effects of the AR-coating beside loss reduction are reduction of the saturation energy and decrease of the recovery time. The latter was confirmed by pump-probe measurements at the SESAM design wavelength of 2040 nm, giving interband relaxation times τ_2 (slow component) of 8.4 ps and 4.1 ps for the uncoated and AR-coated SESAM, respectively. The reflectivity band of the used SESAM, determined by the GaSb/AlAsSb distributed Bragg reflector, extends from 1890 to 2120 nm.

3. Laser setup

An X-shaped cavity was employed during the experiments as shown in Fig. 2. The Ho:YAG ceramic sample was placed at Brewster angle between two dichroic folding mirrors M_1 and M_2 with a separation of ~10 cm (reflectivity: <0.25% at 1908 nm and >99.9% from 2015 nm to 2150 nm; radius of curvature, RoC: −10 cm). In one of the cavity arms, the SESAM served as an end mirror. The folding mirror M_3 with a RoC of −10 cm ensured tight focusing at the position of the SESAM. Wedged output couplers (OCs) were placed at the other end of the cavity. The two arms were nearly balanced in length benefiting from the extended stability range with respect to the tolerated separation of the curved mirrors (M_1,M_2) in the central folding. The resulting total cavity length was 183 cm. For optional wavelength tuning, a 3.2 mm thick quartz plate was inserted close to the OC.

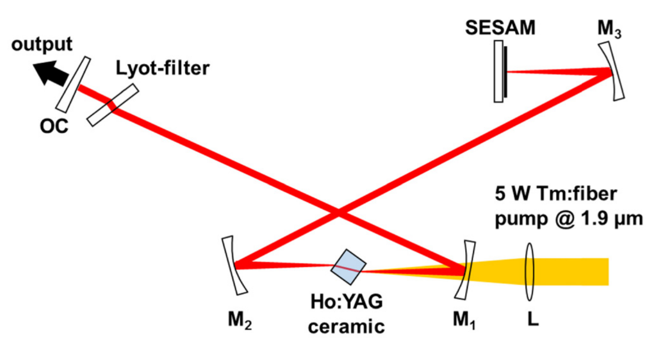

Fig. 2. Scheme of the mode-locked Ho:YAG ceramic laser (L: lens; M1-M3: dichroic folding mirrors; OC: output coupler; Lyot-filter: birefringent filter).

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Tm-fiber lasers are well-siuted pump sources for Ho-doped lasers since they offer a nearly diffraction limited beam quality. Typically a Bragg grating is added for narrowband emission of the Tm:fiber pump laser at the selected wavelength [1]. The pump source was a CW Tm-fiber laser (IPG Photonics) delivering up to 5.2 W output power at 1908 nm with an emission linewidth of 0.3 nm. After the collimating optics, the beam has a diameter of 4.5 mm with a divergence angle of 0.57 mrad and an M^2 of 1.03. The pump beam was focused using a 7-cm lens. The calculated pump beam radius at the input facet of the crystal was 28 µm and the cavity was designed for laser mode radius of 29 µm. The resulting beam radius on the SESAM was 99 µm.

4. Experiment results and discussion

Initially, CW laser operation was studied using a plane high reflecting end mirror instead of M_3 and the SESAM. The single-pass pumped Ho:YAG ceramics absorbed only about 36 ± 1%, because the pump was unpolarized and the sample placed at Brewster angle. By applying different OC transmissions from 0.5% to 5%, the laser delivered a maximum output power of up to 1 W with slope efficiencies between 56% and 71%.

Increasing the output coupler transmission the free-running emission wavelength changes from 2122 to 2097 nm and finally to 2091 nm. In quasi-three level laser systems, such as the Ho:YAG, the free-running emission wavelength depends on the loss in the cavity. In an oscillator with relatively low loss, emission is achieved at longer wavelengths of the gain spectrum. Increasing the cavity loss (such as the output coupling) a higher gain (i.e. inversion level β) is required to reach the laser threshold which is connected with a shift of the emission to shorter wavelengths (Fig. 1(b)). As the cavity loss increased, in the free-running regime a strong tendency of dual-wavelength emission at 2090 and 2096 nm was observed, similar to [11] where up to three wavelengths occurred. This behavior is most likely due to the nature of Ho:YAG and agrees with the calculated gain cross sections in Fig. 1(b) and [7]. The three wavelength emission is expected for β ~0.2 whereas for slightly higher β the two wavelength emission around 2.09 µm is favored.

Implementing the Lyot filter in the cavity (free spectral range: 146 nm), single-wavelength CW tuning from 2008 to 2130 nm was achieved using the 1.5% OC, as shown in Fig. 3. The total CW tuning range of 122 nm is more than twice the value reported so far [33].

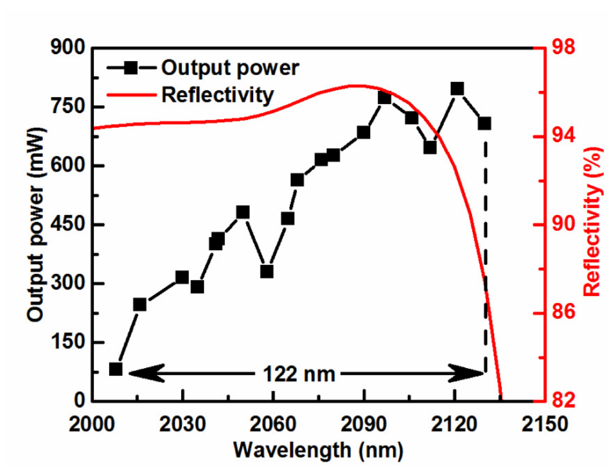

Fig. 3. Spectral tunability of the CW Ho:YAG ceramic laser obtained with a Lyot filter (1.5% OC) and reflectivity curve of the used GaSb-based SESAM.

After introducing the SESAM in the cavity, self-starting CW mode-locked laser operation was achieved for the 1.5% and 0.5% OCs. The graph of the relevant long wavelength part of

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the SESAM reflectivity band is shown in Fig. 3. The results in terms of output power and slope efficiency are shown in Fig. 4. Stable CW mode-locking starts at an intracavity power exceeding 5.3 W. Thus, the threshold was estimated at on-axis SESAM fluences of ~410 μJ/cm^2. When increasing the pump power the laser directly switched from the CW mode to CW mode-locking (Fig. 4). No Q-switched operation or Q-switched mode-locking were observed for the applied pump power range. Using the 1.5% OC, the laser delivered a maximum mode-locked output power of 258 mW with a slope efficiency of 18% for 1.4 W absorbed pump power. The maximum pump power applied with the 0.5% OC was limited to 1.1 W (output power: 128 mW), since damage at the surface of the SESAM was observed. Thus the damage threshold of the SESAM is estimated to be about 1.9 mJ/cm^2 of on-axis fluence. As long as the laser was operated below the fluence value which leads to the damage of the SESAM, the mode-locked laser was very stable. Once the mode-locked operation started, it was maintained without interruption during the daily routine operation.

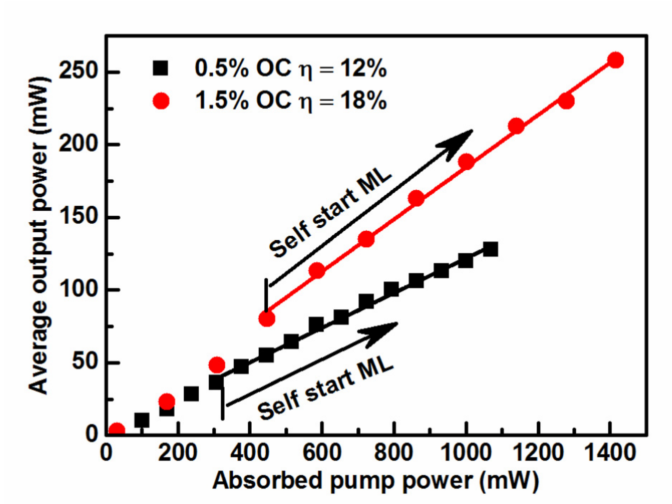

Fig. 4. Output power versus absorbed pump power of the mode-locked Ho:YAG ceramic laser for different output couplers (OCs) without the Lyot filter in the cavity. The vertical lines indicate the transition from CW to clean mode-locked operation (ML – mode locking).

The non-collinear autocorrelation traces and optical spectra of the Ho:YAG ceramic laser are presented in Fig. 5 at maximum output power. As in the CW regime stable dual-wavelength emission centered at 2090 and 2096 nm occurred. Each peak exhibits a spectral width of 1.4 nm (FWHM) for both, the 1.5% and 0.5% OC (Fig. 5(d)). A pulse duration of 7.4 ps is derived from the measured autocorrelation trace (APE *pulse*Check) under the assumption of a sech^2-pulse shape (Figs. 5(a) and 5(b)). The autocorrelation trace is modulated with a frequency of 0.43 THz, which coincides with the spectral difference of the two emission wavelengths (Figs. 5(a) and 5(b)). The depth of this modulation, cf. Figures 5(a) and 5(b), depends on the intensity ratio of the two peaks (Fig. 5(d)). Dual emission of the same pair of wavelengths was reported for the SESAM mode-locked Tm,Ho:YAG laser in [11]. In contrast to our measurement, no modulation of the autocorrelation trace was detected, most likely because of the much longer pulse duration of 57 ps [11]. Such dual-wavelength mode-locking regimes were observed in different spectral ranges and suggested as promising approach for the generation of THz radiation or synchronized sources for double-pulse pump-probe measurements [34–36]. Here we no longer pursue the synchronous dual-wavelength emission aspect, but concentrate on the generation of non-modulated pulses with shorter duration.

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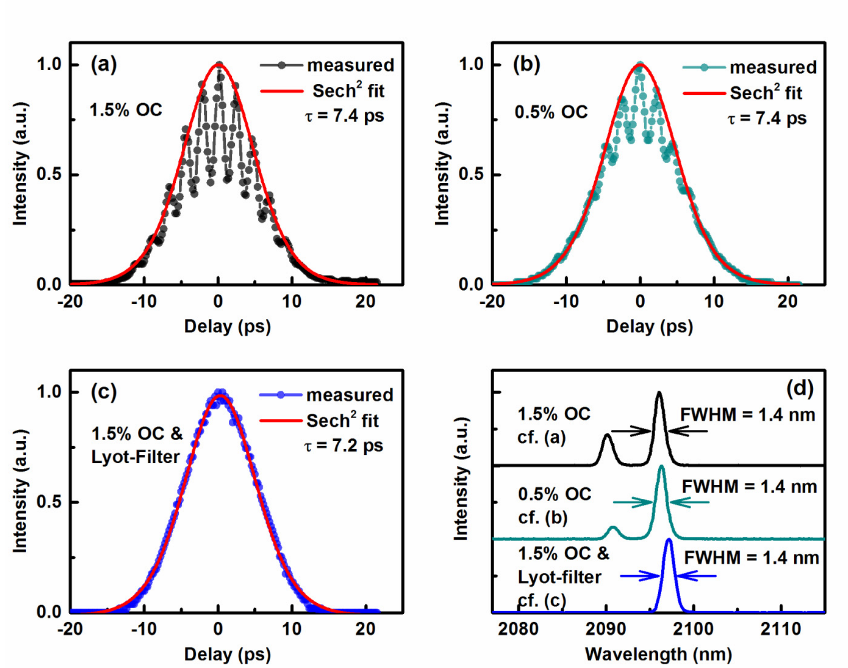

Fig. 5. SESAM mode-locked Ho:YAG ceramic laser. Autocorrelation traces without (a,b) and with a Lyot filter (c) in the cavity (OC: output coupler). (d) Emission spectra corresponding to (a), (b) and (c).

At first we introduced a CaF_2 prisms pair and optionally a knife edge in the arm of the laser cavity containing the OC. Neither the targeted single-wavelength emission nor a significant pulse shortening were achieved despite introducing a large amount of group delay dispersion (up to −1700 fs^2). As next approach we implemented the birefringent (Lyot) filter in the mode-locked cavity and removed the CaF_2 prisms (Fig. 2). In this configuration the dual-wavelength emission was eliminated and clean pulses without modulation were generated at 2096 nm (Figs. 5(c) and 5(d)). The non-modulated pulses are slightly shorter with a duration of 7.2 ps and the time-bandwidth product amounts to 0.69. Undoubtedly, the birefringent filter limits the gain bandwidth and hence the achievable pulse duration to a few ps. However, even in the mode-locked regime it ensures single wavelength emission and broadband tunability. Using the birefringent filter the tunability of the mode-locked Ho:YAG ceramic laser is shown in Fig. 6(a). Mode-locked operation was achieved from 2059 to 2121 nm when applying the 1.5% OC. We have to note that the laser was still pulsing up to 2130 nm, however, stable mode-locking was interrupted. We attribute this instability to the fast drop of the SESAM reflectivity at ~2120 nm (Fig. 3). Furthermore, a local heating of the SESAM at the position of resonator waist can be expected which is accompanied by a slight redshift of the DBR reflection band enabling mode-locking up to 2121 nm. The pulse duration decreases from 15.6 ps at 2121 nm to 2.5 ps at 2065 nm and the maximum output power amounts to 230 mW at 2121 nm. This pulse shortening could be ascribed to an increase of the modulation depth of the SESAM towards shorter wavelengths [10] because it is designed for 2040 nm. The corresponding time-bandwidth products increase with tuning to shorter wavelengths from 0.5 to 0.9 which is about 2–3 times the time-bandwidth limit. We again tried to shorten the pulse duration by introducing the CaF_2 prism pair but almost no influence on the pulse performance was observed, as without the birefringent filter. Using the 0.5% OC the tuning range was similar to that achieved for 1.5% OC, however the shortest pulse duration of 2.1 ps was generated at 2064 nm with 10 mW output power (Fig. 6(b)).

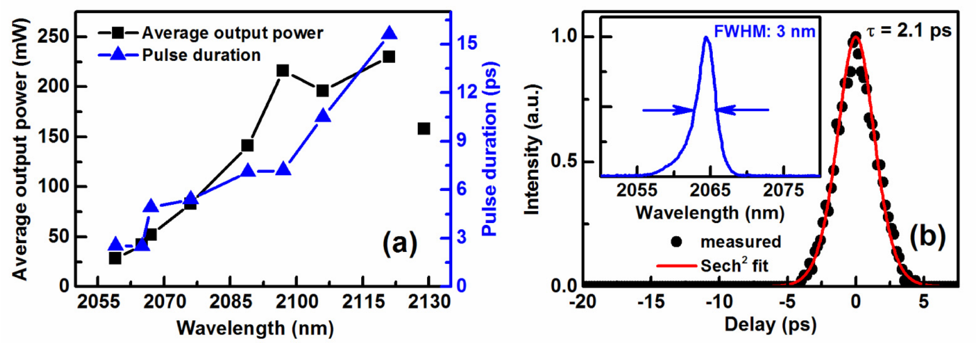

Fig. 6. (a) Spectral tunability of the mode-locked Ho:YAG ceramic laser with the Lyot filter in the cavity (1.5% OC), (b) Autocorrelation trace and emission spectrum (inset) of the shortest pulses (0.5% OC).

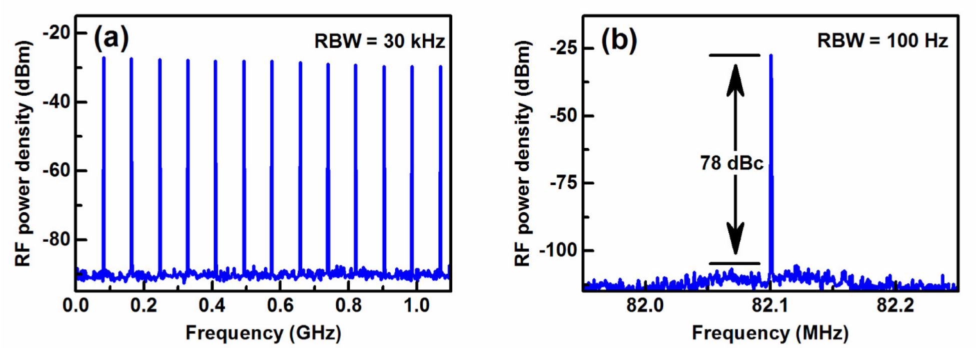

Fig. 7. Radio frequency spectra of the SESAM mode-locked Ho:YAG ceramic laser: (a) 1.1 GHz wide-span, (b) fundamental beat note (RBW: resolution bandwidth).

The stability of the mode-locked Ho:YAG ceramic laser including the birefringent filter was characterized by the measurement of the radio frequency (RF) spectrum and the results are shown in Fig. 7. The narrow band fundamental beat note was at 82.1 MHz with a high extinction ratio of 78 dB above noise level (Fig. 7(b)), measured with a resolution bandwidth of 100 Hz. The wide-span RF measurement extended over 1.1 GHz and the resolution bandwidth was 30 kHz (Fig. 7(a)). Both RF spectra indicated clean CW mode-locking without Q-switching instabilities or any multi-pulse behavior [37].

5. Conclusion

An in-band-pumped 1 at.% Ho:YAG ceramic laser around 2.1 μm has been studied in different operation regimes. For the first time to our knowledge, passive mode-locking is obtained for Ho:YAG at pulse durations as short as 2.1 ps. With respect to the previously reported performance of mode-locked singly Ho-doped lasers, the presented results appear quite promising and are comparable to the best parameters achieved with Ho:YLF [38]. At the Ho:YAG ceramic gain maximum around 2090 nm, a strong tendency of dual-wavelength mode-locking was observed. This feature was successfully suppressed by implementing a birefringent filter in the cavity. Thus, tunable self-starting ultrashort pulse generation was realized in the 2059–2121 nm spectral range. The obtained excellent broadband mode-locking performance outlined by the high extinction ratio of 78 dB above carrier of the first beat note in the RF spectrum and the short pulse durations for Ho:YAG can be ascribed to the used

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near-surface QW SESAM design parameters, like the recovery time and the modulation depth.

Applying such GaSb-SESAMs designed for higher damage threshold and slightly higher modulation depth and an improved dispersion management using alternative materials with high negative GVD for dispersion compensation, we expect further pulse shortening into the sub-ps range with the Ho:YAG ceramic laser.

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