Volume 14, Number 4, 2021. pp. 275-286

Jordan Journal of Physics

ARTICLE

Mid IR Holmium, Praseodymium - doped Fluoride Fiber Laser Pulse Operation

Fadi Qamar

Physics Department, Faculty of Sciences, Damascus University, Damascus, Syria.

Doi: **https://doi.org/10.47011/14.4.1**

Received on: 06/05/2020; Accepted on: 05/11/2020

Abstract: Pulsed operation of a novel single-clad mid IR Ho^{3+}, Pr^{3+} co-doped ZBLAN fiber laser excited by a Nd:YAG laser at 1064 nm has been demonstrated using pulse-pumping. An acousto-optic modulator (AOM) has been used to modulate the CW input pump laser and used in either zero-order or first-order operation. A regular output train of pulses was generated for modulation frequencies over 1 Hz - 100 kHz with zero-order operation of the AOM. A maximum peak power of ~ 50 W and pulse duration of ~200 ns have been obtained for a modulation frequency of 45 kHz and 9.3 W pump power. Single-end and double-end pumping of the first-order AOM operation for the fiber have also been demonstrated to avoid the overheating of the modulator which reduces the modulation efficiency. The same results as the zero AOM operation were obtained when the fiber laser was pumped with a pumping power of about 5 watts.

Keywords: Fiber lasers, Pump pulsed operation, Acousto-optic modulator (AOM), Single-end and double-end pumping.

PACs: Fiber lasers, 42.55.Wd, Acousto-optical devices, 42.79.Jq.

Introduction

Pulsed fiber lasers operating near 3 μm hold potential for various sensing [1], spectroscopy [2], metrology [3] and medical [4,5] applications. All studies so far are concerned with pulsed operation of the Er-doped ZBLAN glass fiber laser emitting at 2.7 μm. The first Q-switched Er - ZBLAN laser was reported in [6], where the gain was switched with two different methods; firstly with an acousto-optic modulator (AOM) yielding a pulse length of ~100ns, peak power of 2.2 W and average powers up to 500 μW; secondly with a rotator mirror, producing a minimum pulse width of 270 ns with repetition rates up to 500 Hz. Passive Q-switching of the Er-doped fluoride fiber laser has been demonstrated [7] using an InAs saturable absorber; this yielded a maximum peak power of 1 W and a pulse energy of 1.25 μJ. The pulse intervals in a multi-mode fiber were found to be much longer compared to a single-mode fiber, indicating better energy storage properties and thus, more efficient Q-switch operation. The limitation of this method was the damage to the InAs absorber at high pump powers. Q-switching of a diode cladding-pumped Er-doped fluoride fiber laser has also been reported [8], with a rotating mirror or an acousto-optic modulator. This generated pulses in the range of 300 - 500 ns, with repetition frequencies between 10 and 136 Hz with the rotating mirror and 1 Hz - 2 kHz with the AOM and produced pulse energies between 1 and 1.5 μJ at an average power of 2 mW (at 2 kHz repetition rate). With these pulse energies, the destruction limit of the fiber was reached.

A pulse-pumped 2.7 μm Er-doped ZBLAN fiber laser has been investigated [9], which was longitudinally pumped by a tuneable, flash-lamp pumped Ti: sapphire pulsed laser operating at a wavelength of around 785 - 795 nm. The

Corresponding Author: Fadi Qamar **Email**: fadiqamar@Hotmail.com

observed relaxation oscillations in the laser output had a peak intensity of approximately 2 kW and a duration of 200 ns when the fiber was pumped by 30 mJ pulses. An energy output of 1.9 mJ at a slope efficiency of 13.5 % with respect to launched pulsed pump energy from a near single transverse mode Er-doped ZBLAN fiber laser was reported. Switching of the output wavelength from 2700 to 2756 and then to 2770 nm was observed in the fiber laser spectrum, attributed to reabsorb losses from the long-lived lower laser level. The limitation of this method is that the output energy is limited by damage of the fiber launch facet due to the short pump-pulse duration. Finally, Q-switched operation of a cladding-pumping Er^{3+}/Pr^{3+} co-doped ZBLAN fiber laser using mechanical chopper has been demonstrated [10]. A pulse energy of 10μJ and 250 ns duration were obtained at a relatively low repetition rate of 500 Hz, while a maximum average power of 19 mW was obtained at the higher repetition rate of 19.5 kHz. The maximum power was limited by the switching speed of the pulsed pump and there was no evidence of saturation in the output power due to ASE or ESA. A gain-switched Er:ZBLAN fiber laser based on an active pulsed diode pump system was also reported [11]. The measured pulse duration was 300 ns and nearly independent of the pump repetition frequency. The maximum obtained peak power was 68 W with 2 W of average power at the repetition frequency of 100 kHz. Recently, many Q-switched operations of Er:ZBLAN fiber laser at 2.8 μm using different methods such as acousto-optic modulator [12] and topological insulator Bi_2Te_3 nanosheets [13] were demonstrated. On the other hand, CW operation of Ho^{3+} and Ho^{3+}, Pr^{3+}-doped ZBLAN fiber lasers has been reported; these are alternative and efficient lasers emitting at 2.85 - 2.87 μm and have been pumped by 1.1μm or 1064nm lasers [14-16]. Passively Q-switched Ho^{3+}-doped fluoride fiber laser using Fe^{2+}:ZnSe crystal and graphene saturable absorbers was latterly reported [17] and 800 ns pulses at 2.93 μm with an energy of 460 nJ and a repetition rate of 105 kHz were obtained. A diode-cladding-pumped mid-infrared passively Q-switched Ho^{3+}-doped fluoride fiber laser using a broad band semiconductor saturable mirror (SESAM) was also demonstrated [18]. Maximum pulse energy of 6.65 μJ with a pulse width of 1.68 μs at a repetition rate of 47.6 kHz was produced at a slope efficiency of 12.1 % with respect to the launched pump power and center wavelength of 2.971 μm. Actively Q-switched Ho^{3+}, Pr^{3+}-doped fluoride fiber laser by a TeO_2 acousto-optic modulator, producing a peak power of 77 W, with a pulse width of 78 ns and a slope efficiency of 20 % with respect to the launched pump power was achieved. The modulator allowed continuous tunability of the pulse repetition frequency from 40 to 300 kHz and the fibre pumped 1150 nm diode laser [19].

In this paper, the first description of pulsed operation of an Ho^{3+}, Pr^{3+}-doped ZBLAN fiber laser emitting at 2.874 μm is reported using low peak power pulse pumped excitation by a 1064 nm Nd: YAG laser. The modulation of the CW input power was controlled by an AOM, which allowed variation of the duration and energy of the pump to obtain optimum gain switched laser. In addition, double-end pumping with CW input into one end has been used to create a gain pedestal onto which the pulsed excitation is impressed.

Experimental

The fiber laser used was a heavily doped single-clad fluoride fiber, manufactured by Fiber-labs, Japan, with concentrations of 30000 ppm molar Ho and 3000 ppm molar Pr. The fiber had a core diameter of 15 μm supporting single mode operation, a numerical aperture (NA) of 0.13 and an intrinsic loss of ~ 30 dB/km at 800 nm. The fiber was pumped by 10 W single transverse mode vertically polarized Nd: YAG laser output operating at 1064 nm. A polarization-insensitive bulk TeO_2 Bragg cell acousto-optic modulator (AOM, NEOS Model N36027) was used to modulate the input beam. The AOM modulator system had the following crystal specifications: transmission of ~93 % andefficiency (loss modulation) of > 50 % at 1064 nm, active aperture of 5 mm, extinction ratio of -76 dB, able to be driven up to 27 MHz and rise/fall times of 182/40 ns and opening times in the order of 50 ns to few microseconds.

The experimental setups are shown in Fig.1.

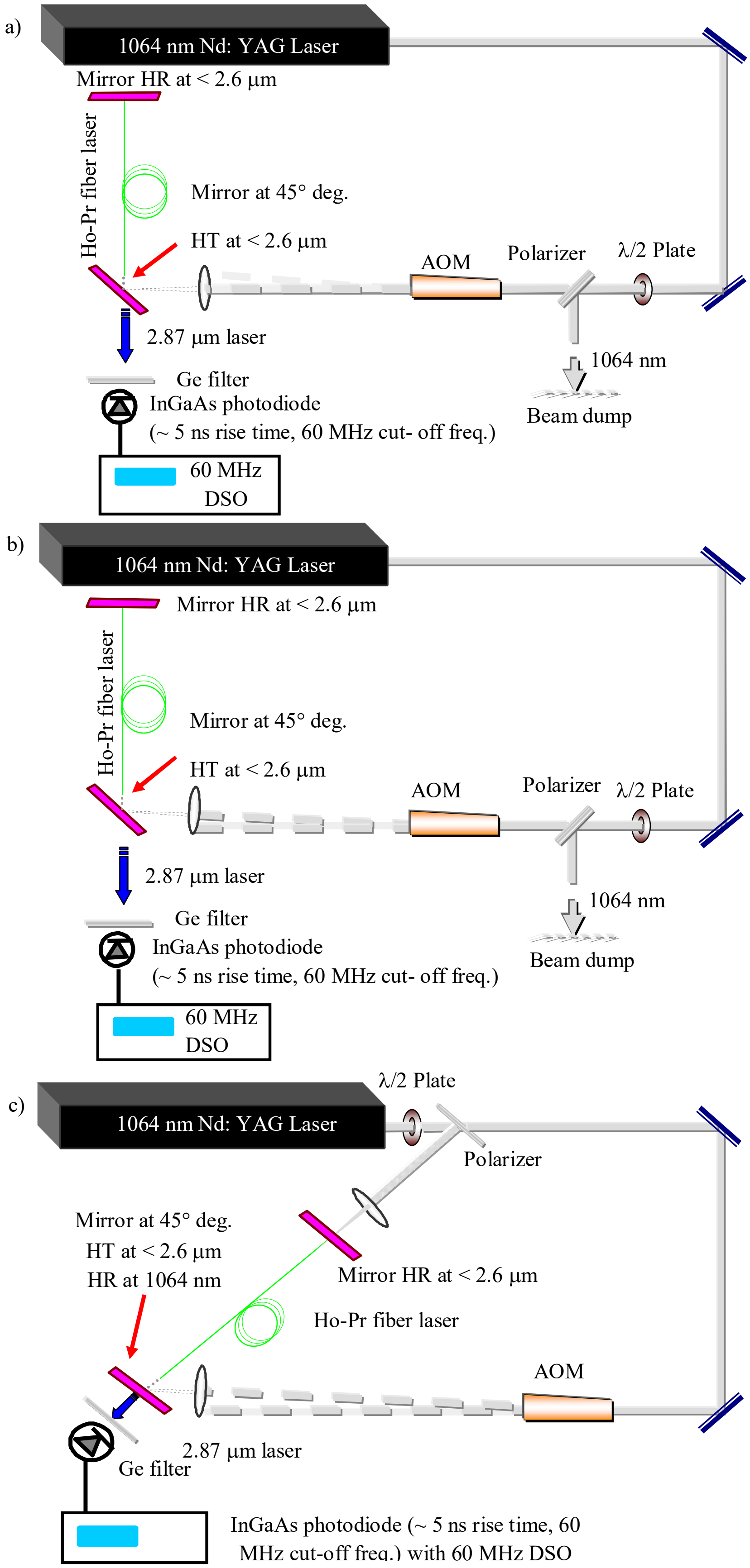


FIG. 1. Experimental setups for pulse pumping a single-clad Ho^{3+}, Pr^{3+} co-doped ZBLAN fiber laser. a) zero-order AOM operation, b) first-order AOM operation, c) first-order AOM operation with simultaneous CW pumping of the second fiber facet.

Three different designs have been used to suit different forms of fiber laser operation. Fig. 1a shows the experimental configuration with zero-order operation of the AOM. The modulated beam was focused by an objective lens with NA of 0.25 and reflected by a 45º dichroic mirror for launching into the fiber. The dichroic mirror was HR (~99 %) at the pump wavelength and HT (~97 %) with an anti-reflection coating at the lasing wavelength. The distal facet of the fiber was butted with a mirror HR at both the pump and lasing wavelengths, so that the cavity consisted of Fresnel reflection and a highly reflecting mirror. The output temporal profile of the laser was measured using an unamplified, liquid nitrogen-cooled InAs photodiode (Judson J12D) with a response time of approximately 2 ns, connected to a 60 MHz digital storage oscilloscope (Tektronix TDS210). A Ge filter before the detector was required to eliminate the input pump. Fig. 1b shows a similar design, but with first-order operation of the AOM, where the diffracted light is launched into the fiber. In Fig. 1c, the setup is re-arranged to be double end-pumped, allowing a low intensity of CW pump light into the second facet of the fiber. A focusing lens with NA 0.25 has been used to launch the reflected pump light transmitting from the polarizer into the second facet of the fiber which butted to a mirror; this was HT at the pump wavelength and HR at lasing wavelength. The half wave plate and the polarizer in these arrangements have been used to control the pump power as well as to control the double-end pumping in the third design.

Pulsed Fiber Laser Operation, Results and Discussions

Zero-order AOM Operation

The zero-order operation of the AOM was applied in the first experiment, where the laser intensity built up with the AOM in the off position allowing all the input power to be launched into the fiber. On the other hand, when the modulator switched to the on position, more than 50 % of the input power was diffracted with the remainder being transmitted to be stored inside the fiber until it was released as a narrow pulse. The method required the AOM to be kept in the on position for a period of time determined by the modulation frequency, so that power was stored inside the fiber and then it was switched to the off position for another period of time (defining the opening time). This was determined experimentally by adjusting the modulated pump pulse width from the pulse generator to avoid multi-pulse emissions and thus produce single, short, high-peak power pulses and hence achieve efficient pulsed emission. The opening time was adjusted dependent on the length of the fiber as well as on the doping concentration and pump power.

Fig. 2a shows that the opening time decreased for shorter lengths. For a shorter length of fiber, a greater energy density can be stored (at the same time) compared with a longer fiber. As the amount of stored energy increased, the time required to achieve the population inversion inside the fiber decreased so that a reduced opening time was required. Fig. 2b shows that a shorter opening time is necessary for a single pulse to be produced when more pump power is used. Increasing the input power leads to faster development of population inversion and reduced radiative loss from the fiber, thus a shorter opening time is required to avoid multiple-pulse emission.

The peak power and pulse duration were also studied as a function of the modulation frequency for two fiber lengths of 12 m and 9.25 m (which is the optimum length of the CW process) pumped by a 9.3 watt laser beam, as shown in Fig. 3a and Fig. 3 b.

Comparing the behavior shown in these figures, it can be deduced that the peak power of the pulses increased and the pulse duration decreased when shorter length fiber or higher pump power was used. Individually, each fig. shows that changes in the duration and the peak power are small for low modulation frequencies, while they increase at high frequency towards 40 - 45 kHz and then decrease again. This suggests that the system is most efficient when the modulation frequency is in the range of the relaxation oscillation frequency of the system, which is between 40 - 80 kHz. The range of the relaxation oscillation frequency was measured for the long opening period of AOM. The shorter pulse duration of 200 ns, the higher peak power ~ 50 W with about 93 % pulse-to-pulse stability and average power of 450 mW were obtained for the 9.25 m fiber length and at a modulation frequency of 45 kHz, as shown in Fig. 4.

However the optimum length of the fiber for pulsed operation has not been determined in this experiment. This method has the advantage that no extra components are required inside the cavity to achieve the pulsed operation; it is straight forward to operate and align and leads to achieve a compact pulsed fiber system, especially when combined with diode pumping. On the other hand, a disadvantage of this method is that high-efficiency pulsing occurs for higher modulation frequencies, even though the pulsing starts at a low repetition rate (1 Hz).

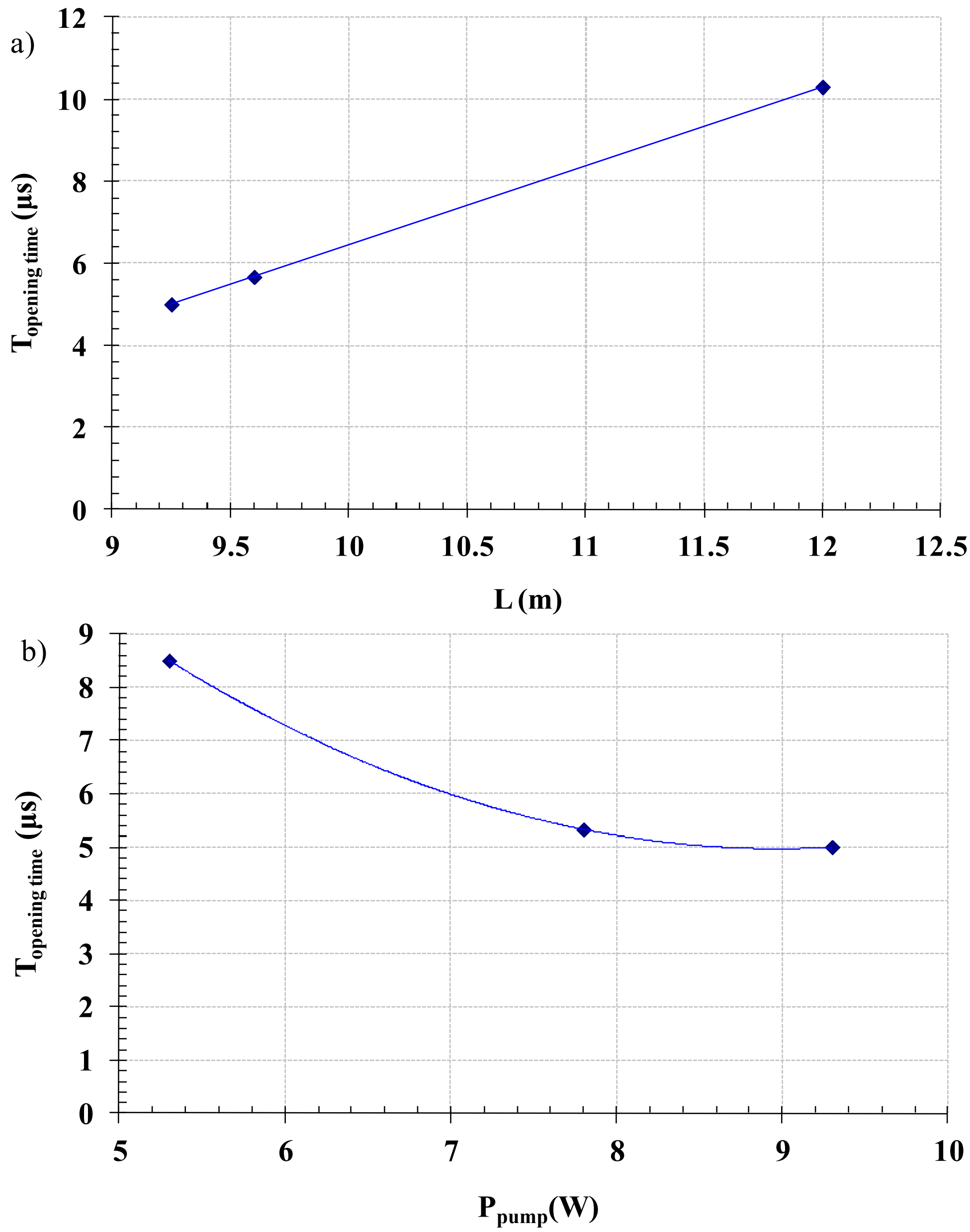


FIG. 2. Opening time of zero-order AOM operation required to produce a single pulse at 50 kHz modulation frequency as a function of a) fiber length and b) pump power.

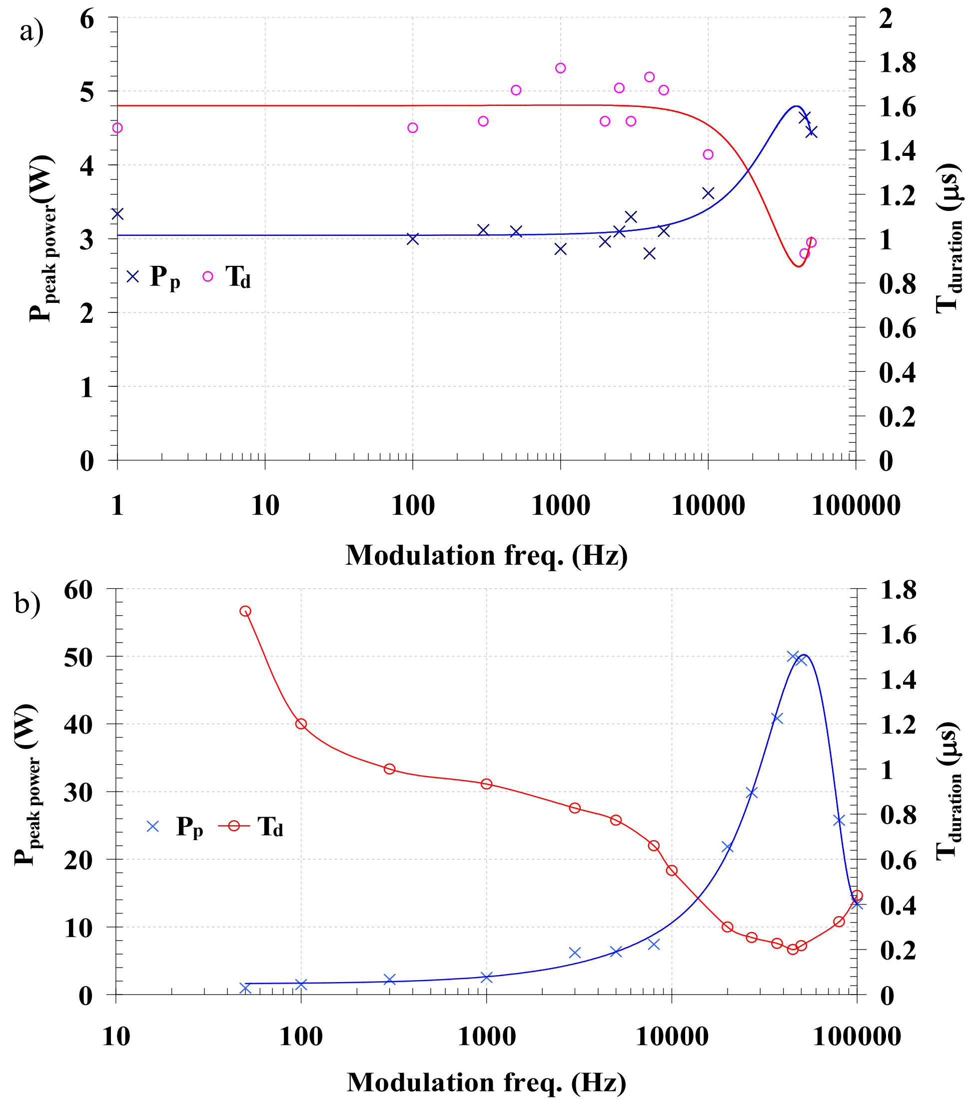


FIG. 3. Peak power and pulse duration as a function of modulation frequency for zero-order AOM operation and for a) 12 m fiber length and 9.3 W pump power and b) 9.25 m fiber length and pump power of 9.3 W.

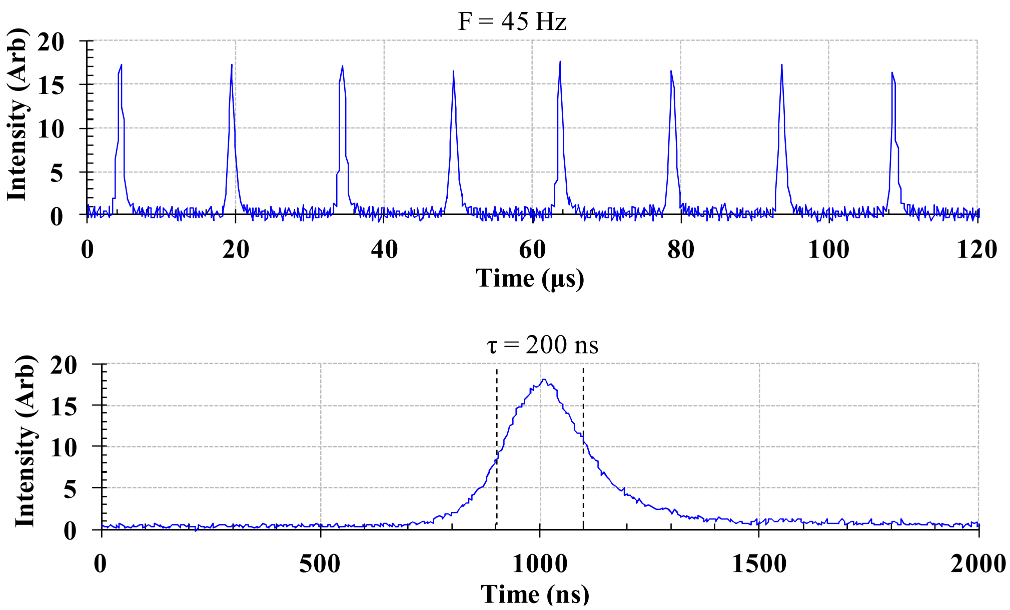


FIG. 4. A pulse train for zero-order AOM operation with modulation frequency of 45 kHz; the duration of each pulse is 200 ns.

First-order AOM Operation

Operating the AOM in zero-order results in overheating of the modulator, which reduces the modulation efficiency and thus cooling is required. Another major disadvantage is that, in this mode, the stored power (non - diffracted power) cannot be controlled separately, unless the input power is reduced or a longer fiber is used. Both solutions will lower the overall efficiency of the laser. Controlling the amount of non-diffracted power is important in order to avoid simultaneous CW and pulsed lasing, as well as to prevent extra pulses to be created in between the main switched pulses. However, the amount of non-diffracted power also affects the pulse-to-pulse stability and needs to be adjusted for high stability.

The dependence of efficient and stable pulse operation on the stored energy was demonstrated experimentally using first-order operation of the AOM with single-end pumping (SEP) and with double-end pumping (DEP). The simultaneous pumping into the second end was used to vary the energy that was stored in the fiber.

In first-order operation without DEP, only the diffracted power is launched into the fiber, so that pumping of the fiber will occur when the modulator is on and the time required for lasing depends on the build-up time of the laser intensity and on the modulation frequency. Thus, the opening time should be adjusted each time the modulation frequency changes to obtain a single pulse train. The value of the opening time as a function of modulation frequency has been measured for the 13.25 m and 9.25 m fiber lengths, as shown in Fig. 5. For the 13.25 m fiber, Fig. 5a, the opening time for 1Hz modulation frequency was 480 μs, while it was only 16 μs at a modulation frequency of 50 kHz. In comparison, for the 9.25 m length, the opening time becomes 300 μs at 1 Hz and 8 μs at 50 kHz modulation frequency. Thus, using a shorter fiber results in reduction of the opening time; that is because the energy density which is required for pulse operation in a short fiber is less than the energy required for a longer fiber.

Fig. 5b shows the comparison between first-order operation when there is no CW pumping of the second facet of the fiber and when this end is pumped by a 300 mW CW laser beam. It shows that the pumping of both ends helped stabilize the output and fixed the opening time that was required for pulsed operation at one value of ≈ 8 μs for all modulation frequencies.

As a result, pumping both ends of the fiber increases stored energy in the fiber which, without second facet pumping (SEP) in first-order AOM operation, depends only on the length of the modulated pulse which is diffracted from the AOM. The power which is pumped into the second facet has the same function as the CW leakage power in zero-order operation under AOM-on operation. To observe the effect of CW power pumping on the performance of the system, the power pumped into the second facet of the fiber (SEP) has been changed when using a short fiber with 1.5 m length (Fig. 6). It was found that, with SEP, a pure CW output was obtained, Fig. 6a. Applying a small degree of second facet pumping (SFP) power resulted in pulsed operation of the system. A train of pulses has been obtained for feedback power up to 2W and 5 kHz modulation frequency, Fig. 6b. Providing more SFP resulted in a multiple pulsing train, Fig. 6c; further increase in SFP leads to quasi-CW operation, Fig. 6d and then to CW operation of the output, Fig. 6e.

The peak power and pulse duration have been measured as a function of modulation frequency for both conditions; first-order operation without SFP and with 300 mW SFP pump. A fiber length of 9.25 m has been used, which is near to the optimum length for CW operation when the pump power was 9.3 W. Maximum peak pulse powers of 3.3 W and 2.7 W, minimum pulse durations of 1.01 μs and 1.03 μs, as well as average powers of 211 and 266 mW have been obtained for operation with 300 mW SFP and without SFP, respectively. The last result suggests that the amount of the modulation loss should be chosen carefully to ensure successful pulsed operation, especially if the AOM will be used in transmission (zero-order) mode of operation.

Fig. 7 shows that the peak power of the pulse improved with SFP, provided the pulse duration is nearly the same. Pulse-to-pulse stability ratios with and without SFP were 95 % and 92.5 %, respectively.

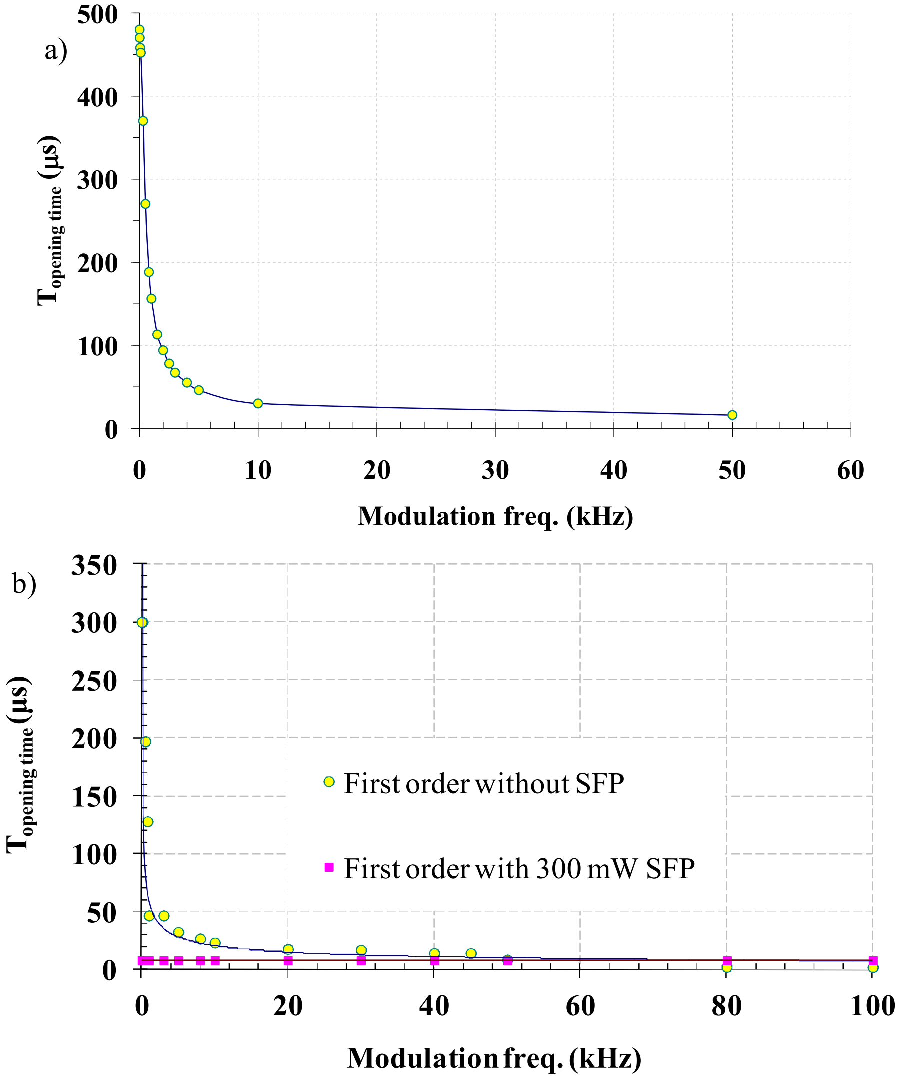


FIG. 5. Opening time as a function of frequency modulation for first-order AOM operation, (a) 13.25 m fiber length, b) 9.25 m fiber length, without second facet pumping (SFP) and with 300 mW SFP.

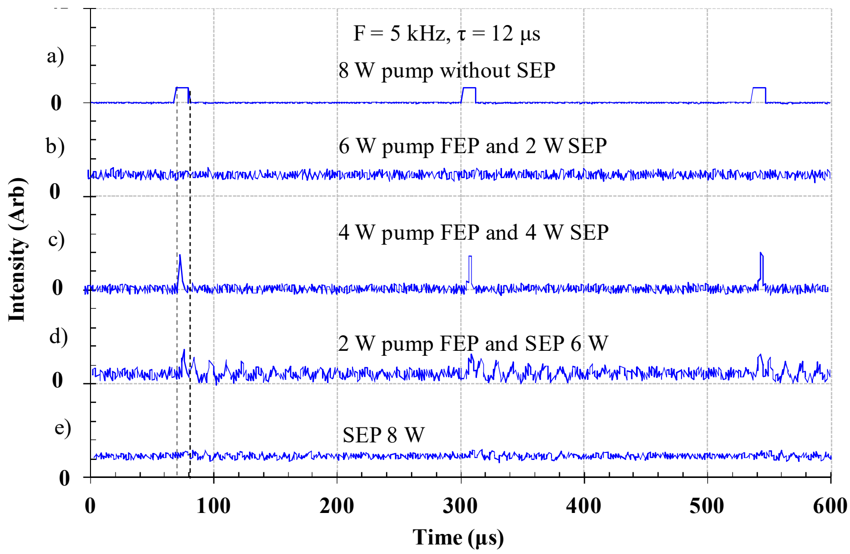
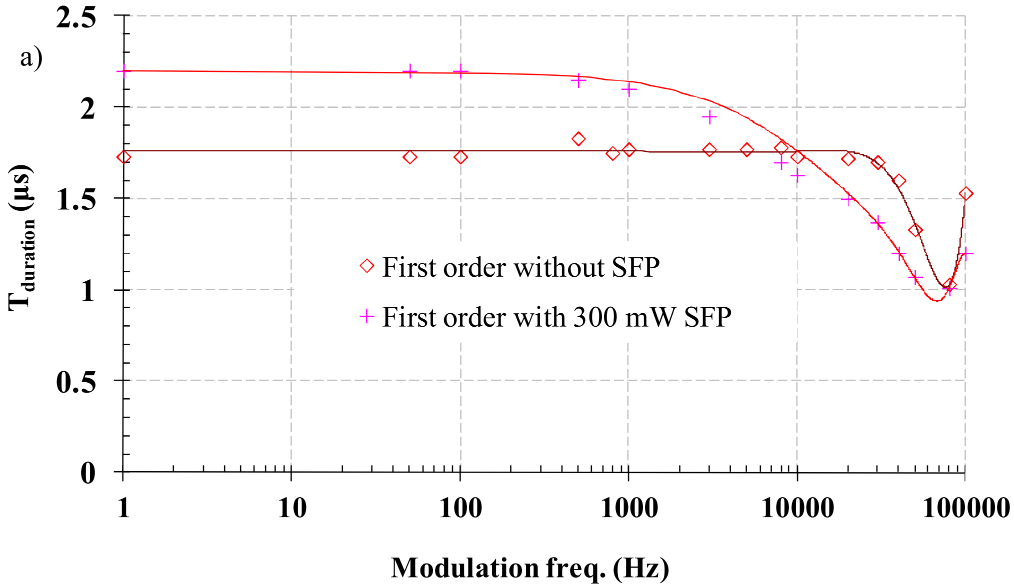


FIG. 6. Temporal profiles of the output of the laser for changes in the degree of double-end pumping, first-order AOM operation for fiber length of 1.5 m. a) CW output, when small opening time is applied with single-end pumping (SEP), b) train of pulses when less than 2 W second facet pumping (SFP) is applied, with 6 W first-end pumping (FEP), c) train of relaxation oscillations for 4W SFP, d) quasi-CW and e) CW output with less than 6W SFP pumping.



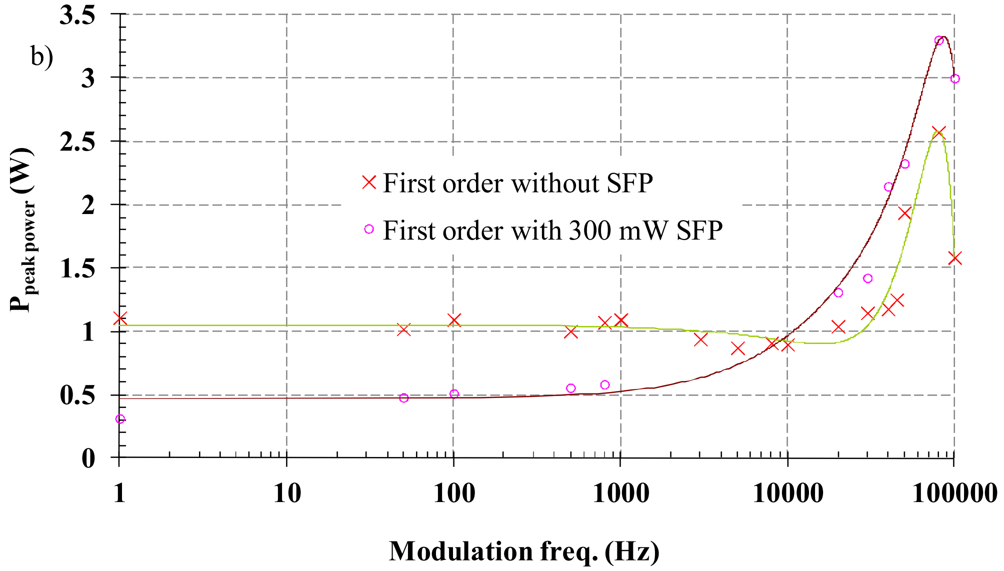


FIG. 7. The comparison between a) pulse durations and b) peak powers as a function of modulation frequency for first-order AOM operation with 300 mW SFP and without SFP, respectively.

Fig. 8 shows a typical pulse train with modulation frequency of 80 kHz and a single-pulse duration of 1.01 µs. A train of short-duration sub-pulses was found within the main pulses. The study of self-locking in this fiber is out of the scope of this paper and will be reported in detail in another paper.

Since only ~50 % of the pump power is diffracted in first-order AOM operation, the first-order AOM results were comparable to the zero-order AOM results when the fiber was pumped at ~5 W (Fig.9).

The highest peak power and the lowest pulse duration values for the first-order AOM operation, when pumped at ~9 W with SFP of 300mW, are found to be consistent with the values obtained for zero-order AOM operation when pumped at 5 W; however, a higher modulation frequency is required to reach these values in first-order AOM operation.

With pulsed pumping, the fiber laser output is, in general, characterized by a series of relaxation oscillations which, at a certain launched pump energy, show good pulse-to-pulse reproducibility. The 1/e damping time of these oscillations can be given as [20]:

$$\tau_{damping} = (\tau_{ul} / r) \qquad (1)$$

where r is the pump-to-threshold ratio and τ_{ul} is the lifetime of the upper laser level. The upper laser level lifetime is ~ 300 µs and the pump ratio r is assumed to be 16 for zero-order AOM operation, so that $\tau_{damping} \sim 18.7$ µs. This value is in the range of the values found experimentally of between 15 - 22 µs. Thus, from Eq. (1), stronger pumping shows fast decay until, for a certain pump power, the output becomes CW. The reduction in pump power can be achieved by reducing the opening time T_{ot}. The pulsed behaviour of the laser can be well understood by comparing the opening time of the AOM with the pulse build-up time T_{bu} after the switch is opened. T_{bu} can be calculated by [21]:

$$T_{bu} \approx (25 \pm 5)\, \tau_c /(r-1) \qquad (2)$$

Here, τ_c is the round-trip period, which is about 93 ns for a fiber laser length of 9.25 m. The build-up time for the previous length of the fiber is in the range of ≈ 0.155 µs and shows good agreement with the experimental results, which are in the range of 0 - 2 µs, dependent on the modulation frequency.

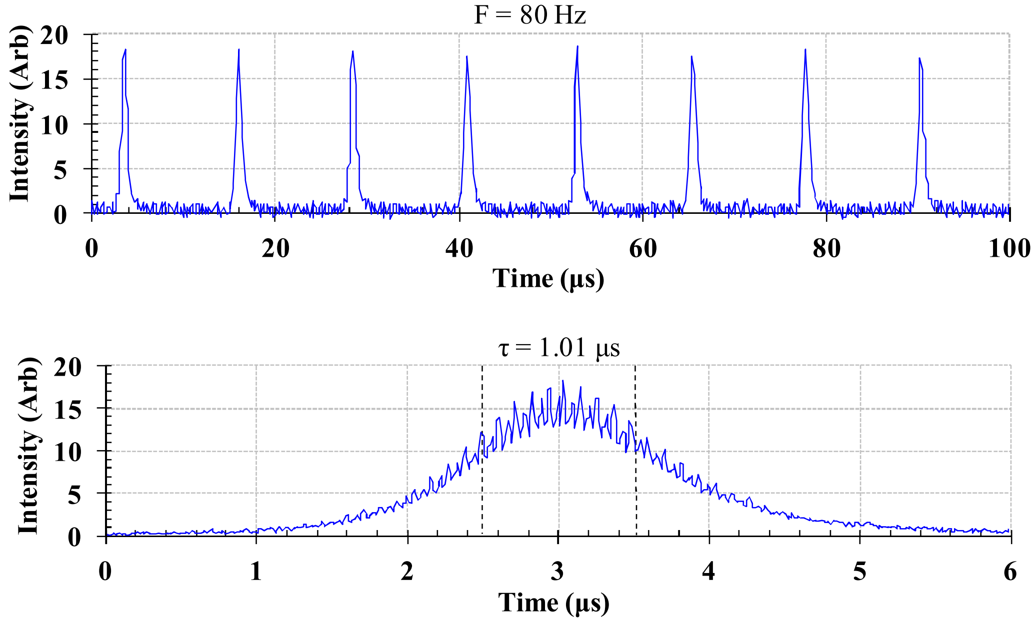


FIG. 8. Temporal profiles for first-order AOM operation: a pulse train with a modulation frequency of 80 kHz and a single pulse with a duration of 1.01 µs.

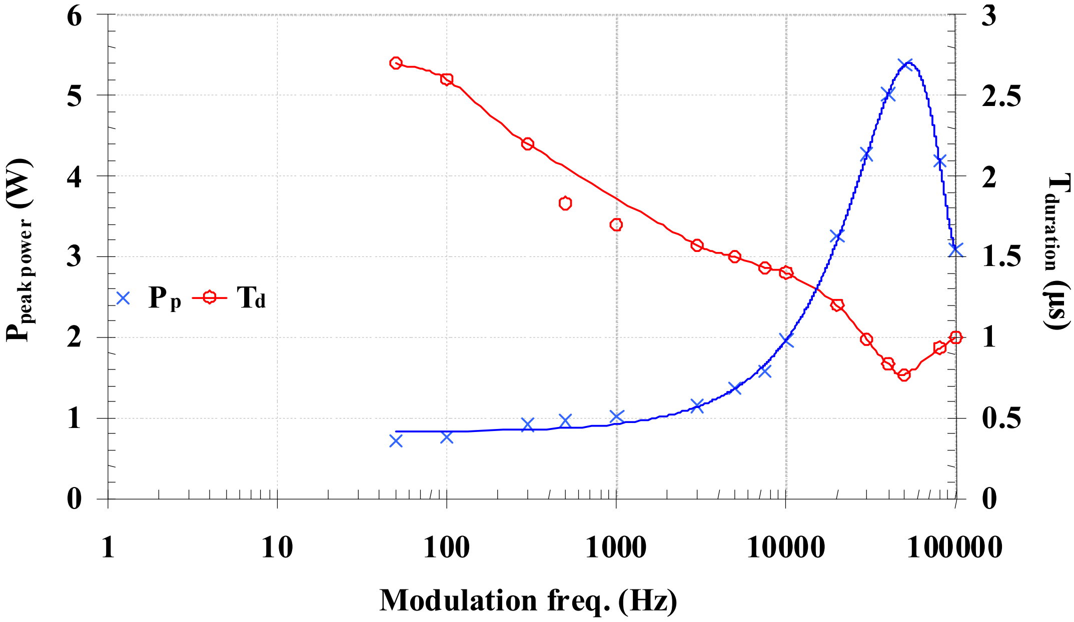


FIG. 9. Peak power and pulse duration as a function of modulation frequency for zero-order AOM operation and for 9.25 m and 5 W pump power.

For opening times longer than the build-up time, $T_{ot} > T_{bu}$, and shorter than the damping time, the formation of the pulse is undisturbed and smooth gain-switched pulses are generated. Multiple pulses or relaxation-oscillation pulses with and without CW in the output appear for opening times longer than the damping time. When the opening time is equal to, or slightly shorter than the build-up time, $T_{ot} \leq T_{bu}$; i.e., a critical opening time, a high-intensity pulse does not have enough time to form and, in consequence, pulses with unstable and reduced amplitude are emitted. The critical opening time is equal to the build-up time and is defined very sharply and can be measured within ± 5 - 10 % accuracy. The build-up time increases at higher repetition rate due to the reduction in the population inversion induced by the pumping light [22]. At low repetition rates (below 40 kHz), the build-up time for a particular cavity configuration remains nearly constant due to the effect of population inversion saturation.

Acousto-optic modulation (AOM) to switch the cavity finesse has been the preferred method of Q-switching in fiber laser and has been used in one of two configurations, zero- or first-order modes. Such modulators offer the advantage of short switching times and electronic control of both the repetition rate and mark-to-space ratio. Their main disadvantage is limited diffraction efficiency, resulting in an increase in the transmitted pump power (CW base intensity) for zero-order operation when the modulator is set to the on position (i.e., almost the light should be diffracted outside the fiber); this transmitted power might become sufficient to set off CW lasing. The pump power must therefore be kept low enough to avoid CW lasing, thus effectively putting an upper limit on the maximum energy and peak power of the gain-switched pulses. First-order operation of the AOM is one effective solution to this problem, but in this case, suppression of CW oscillation is bought at the expense of significantly increased loss in launched power. In the zero-order configuration, the loss is due just to the transmission loss of the modulator, of order of 0.3 dB. In the first-order configuration, the loss is given by the product of the transmission loss and the diffraction efficiency, of the order of 3.3 dB. Since the stored power comes only from the diffracted light, then more input power is needed to reach the lasing threshold. Providing SFP is an effective solution to lower the threshold and improve the pulsed efficiency. First-order operation offers another advantage that the AOM is on only for a small fraction of time. This narrow time window reduces problems associated with thermal effects in the acousto-optic material, which have been seen in this system under zero-order operation.

Conclusion

A novel single-clad Ho^{3+}, Pr^{3+} co-doped ZBLAN fiber laser pumped by a CW Nd: YAG laser at 1064 nm has been pulsed using pulse pump extraction. An AOM with a modulation efficiency of more than 50 % at 1064 nm has been utilized to modulate the CW pump. The AOM is able to generate modulated pulses ranging from a few ns to sub-ms at frequencies from 1Hz to 27 MHz. Operation of the AOM in zero order and in first-order has been demonstrated. A train of pulses of 200 ns duration, 50 W peak power and 450 mW average power at 45 kHz modulation frequency has been obtained for zero-order operation and an un-optimized fiber length of 9.25 m. No evidence of secondary pulses or CW lasing in zero-order AOM operation has been observed, suggesting that the pump power is completely absorbed inside the fiber and there is no need for further reduction in the pump power to avoid multiple pulsing. Pumping of both facets of the fiber in first-order AOM operation has been used to determine the best ratio between the modulated pump pulse and the CW base intensity of the pump power that is required for efficient pulsed operation.

References

[1] Bawden, N., Matsukuma, H., Henderson-Sapir, O., Klantsataya, E., Tokita, S. and Ottaway, D.J., Optics Letters, 43 (11) (2018) 2724.

[2] Tittel, F.K., Richter, D. and Fried, A., Topics Appl. Phys., 89 (2003) 445.

[3] Keilmann, F. and Amarie, S., Journal of Infrared, Millimeter and Terahertz Waves, 33 (2012) 479.

[4] Petersen, C.R., Møller, U., Kubat, I., Zhou, B.S., Dupont, Ramsay, J., Enson, T., Sujecki, S., Abdel-Moneim, N., Tang, Z., Furniss, D., Seddon, A. and Bang, O., Nature Photonics, 8 (2014) 830.

[5] Abu-Sardanah, S.O., Subramaniam, C., Abbasi, S. and Haji Reza, P., Proceedings, Photons Plus Ultrasound: Imaging and Sensing, 11240 (2020).

[6] Frerichs, C. and Tauermann, T., Electron. Lett., 30 (1994) 706.

[7] Frerichs, C. and Unrau, U.B., Opt. Fib. Tech.: Mat., Dev. and Sys., 2 (1996) 358.

[8] Huber, T., Luthy, W., Weber, H.P. and Hochstrasser, D.F., Opt. and Quantum Electron., 31 (1999) 1171.

[9] Dickinson, B.C., Golding, P.S., Jackson, S.D. and King, T.A., Conference on Lasers and Electro-Optics (CLEO 2000). Technical Digest, 39 (2000) 77.

[10] Coleman, D.J., King, T.A., Do-Kyeong, K. and Jongmin, L., Opt. Commun., 236 (2004) 379.

[11] Gorjan, M., Petkovšek, R., Marinček, M. and Čopič, M., Opt. Let., 36 (2011) 1923.

[12] Tokita, M., Murakami, M., Shimizu, S., Hashida, M. and Sakabe, S., Opt. Let., 36 (2011) 2812.

[13] Tang, P., Wu, M., Wang, Q., Miao, L., Huang, B., Liu, J., Zhao, C. and Wen, S., IEEE Photonics Technology Let., 28 (2016) 1573.

[14] Sumiyoshi, T., Sekita, H., Arai, T., Sato, S., Ishihara, M. and Kikuchi, M., IEEE J. Select. Top. in Quantum Electron., 5 (1999) 936.

[15] Jackson, S.D., Opt. Let., 29, (2004) 334.

[16] Qamar, F.Z., King, T.A., Jackson, S.D. and Tsang, Y.H., Journal of Light-wave Tech., 23 (2005) 4315.

[17] Zhu, G., Zhu, X., Balakrishnan, K., Norwood, R.A. and Peyghambarian, N., Opt. Matt. Exp., 3 (2013) 1365.

[18] Li1, J.F., Luo, H.Y., He, Y.L., Liu, Y., Zhang, L., Zhou, K.M., Rozhin, A.G. and Turistyn, S.K., Las. Phys. Let., 11 (2014) 065102.

[19] Hu, T., Hudson, D.D. and Jackson, S.D., Opt. Lett., 38 (2012) 2145.

[20] Siegman, A.E. “Lasers”. (Oxford: Oxford University Press, 1986) p. 414.

[21] Morkel, P.R., Jedrzejewski, K.P., Taylor, E.R. and Payne, D.N., IEEE Photon. Tech. Lett., 4 (1992) 545.

[22] Myslinski, P., Chrostowski, J., Koningstein, J.A. and Simpson, J.R., IEEE J. Quantum Electron., 28 (1992) 371.