Numerical Design of a Gain-Switched Pulsed Laser at 3.92 μm Wavelength Based on a Ho3+-Doped Fluoroindate Fiber

Antonella Maria Loconsole ⊗, Mario Christian Falconi, Vincenza Portosi ⊗, and Francesco Prudenzano ⊗, Member, IEEE

Abstract—A gain-switched pulsed laser based on a commercial, heavily holmium-doped fluoroindate glass fiber, is designed to emit in the middle-infrared range, at the wavelength λ = 3.92 μm. The laser, pumped at λ = 888 nm, is modeled by a six-level system, by taking into account experimental spectroscopic parameters, to identify a feasible laser configuration. An output signal peak power of about P^peak = 14.02 W with a full width at half maximum (FWHM) pulse duration less than τs = 73 ns and pulse energy E_τ = 1.214 μJ is predicted, by considering an input peak power of P_pump = 10 W, and pump repetition rate of f = 100 kHz, by employing a 8 cm-long fluoroindate fiber with holmium concentration N_{Ho} = 100 000 ppm. The obtained result encourages the construction of a pulsed laser based on commercially available optical fiber, for applications in different fields as sensing and biomedicine.

Index Terms—Electromagnetic design, fiber laser, fluoroindate glass, gain switching, holmium, middle infrared.

I. INTRODUCTION

PULSED lasers in the middle-infrared (Mid-IR) wavelength range find wide application in several fields, including free-space communications, remote sensing, biological sensing, medical diagnostics and surgery, agri-food and environmental monitoring since many chemical molecules show Mid-IR absorption [1]–[8]. Those potential applications have attracted great research interest towards fiber lasers emitting at wavelengths beyond 3 μm. During the recent years, a huge quantity of fiber lasers has been constructed by using different host materials which include silica, germanate, tellurite, ZBLAN or fluoroindate glasses. These glasses have been doped/co-doped with different rare-earth ions such as erbium, ytterbium, dysprosium, thulium, holmium, and praseodymium, to obtain emission at different wavelengths [9]–[13]. Great research interest was focused on Er3+-doped fluoride fiber, since emission at about λ = 2.8 μm and λ = 3.5 μm allowed to obtain intriguing laser in continuous wave (CW), gain-switched, and Q-switched regime [14]–[16]. In particular, in [15] a gain-switched fiber laser operating near λ = 3.5 μm via a dual-wavelength pumping scheme was obtained in an erbium-doped fluorozirconate fiber, with stable pulses with repetition rates ranging between 15 and 20 kHz and laser efficiency of η = 4.7%. Fluoroindate optical fibers can exhibit attenuation much smaller with respect to the fluoride ones at longer wavelength, beyond λ = 3.3/3.5 μm, also with reference to available on market products [17]. They exhibit very promising performances in terms of high transparency, with reduced optical attenuation α ≈ 0.2 dB/m from ultra-violet (UV) to Mid-IR range [18]. Therefore, they can enable promising applications in the 3 – 5 μm atmospheric transparency window and in an important part of the molecular fingerprint region. During the last years, rare-earth doped fluoroindate glasses have been spectroscopically investigated with the aim of finding new pumping schemes and operating wavelengths [19]–[24]. As an example, dysprosium and holmium ions allow emission at wavelengths beyond 3 μm [12], [25]. Recently, holmium-doped fluoroindate fibers have been characterized [25]–[29] and CW lasers emitting at λ_s = 2.875 μm [30] and λ_s = 3.92 μm [31], [32], pumped at λ_p = 1120 nm and λ_p = 888 nm respectively, have been demonstrated. For that pertaining the pulsed laser operation, emissions at the wavelength λ_s = 2.106 μm [33] and in the λ_s = 2.95 – 3.015 μm range [34] have been obtained. The literature results reported in [28]–[31], showing the feasibility of CW laser emission in holmium-doped fluoroindate optical fibers, encourage the investigation/prediction of the pulsed operation with these optical fibers as an alternative to erbium-doped fluoride ones [15], [16].

In this work, for the first time to the best of our knowledge, the design of a heavily holmium-doped fluoroindate fiber, pumped at λ_p = 888 nm, is proposed to obtain laser pulses at λ_s = 3.92 μm. By using a homemade numerical solver, the pulsed laser behavior is realistically investigated and optimized, employing measured spectroscopic parameter taken from literature [28], [29]. The developed numerical solver is well validated. The employed design approach is similar to that used in [8], where a gain-switched pulsed laser, based on a Dy3+:ZBLAN fiber was suggested and then successfully constructed exploiting.
et al. W(1d) g = −1 (1) g is the light W−(2) + can be modeled by considering a six-levels sys-
are the branching ratios, are the normalized transverse intensity =3 (transition 4-3, bold red line), radiative and nonradiative decays, excited state absorption (ESA) transition 3-6, bold black line), cross-relaxation (CR) (blue and green dashed lines), and energy transfer up-conversion (ETU) (red solid lines).

the same laser transition, even if the pumping wavelength was different [35], [36], with a good agreement between simulation and experimental results. The obtained results are interesting since, until now, only CW laser based on the same commercial Ho3+ doped fluorozirconate fiber, has been designed [32] or fabricated [31]. Moreover, the practical interest of this work lies in the need of fulfilling accurately the optimized laser parameters identified in the proposed design, in order to construct a pulsed laser in the stable single pulse regime based on a commercial fiber. The simulated performance, in term of laser efficiency are comparable with those obtained by considered other promising dopants and glasses, e.g., the erbium doped fluoroindate fibers reported in [15].

II. RECALL OF THEORY

The Ho3+ doped fluorozirconate fiber stimulated emission at λs = 3.92 μm can be modeled by considering a six-levels system [29], pumped at λp = 888 nm. The complete level scheme, including all the main phenomena, is reported in Fig. 1. The six-level model is employed instead of the five-level model proposed in [28], [31] because it allows an accurate simulation. It is validated by simulating the CW laser presented in [31], obtaining results in good agreement, as reported in the next section, while the five-level model is not suitable and wrong results are obtained in the cases here investigated. Level 5I4 and level 5I5 are degenerate and are considered as single level 4 as reported in [28], [29]. The energy transfer up-conversion phenomenon between level 1 and level 3, starting from level 2, even if included in the model of [29], is here neglected since this approximation does not affect the simulation results. The other light-rare earth interactions taken into account are pump absorption, stimulated emission, radiative and nonradiative decays, excited state absorption (ESA), cross-relaxation (CR), and energy transfer up-conversion (ETU) due to the high Ho3+ ions concentration that will be simulated.

By following the rate equations approach [11], [13], [37], the energy level populations N1, . . . , N6 can be written as a nonlinear system,

$$\frac{\partial N_1}{\partial t} = -W_{14} N_1 + W_{41} N_4 + A_{61} N_6 + A_{31} N_3 + A_{41} N_4$$

$$+ A_{31} N_3 + A_{21} N_2 + K N_3^{\frac{1}{3}} - W_{CR1} N_1 N_4 - W_{CR2} N_1 N_6$$

$$+ 2W_{CR1} N_1 N_4 + W_{CR2} N_1 N_6$$

$$\frac{\partial N_2}{\partial t} = -\frac{1}{\tau_{R2}} N_2 + A_{62} N_6 + A_{32} N_3 + A_{42} N_4 + A_{32} N_3$$

$$+ 2W_{CR1} N_1 N_4 + W_{CR2} N_1 N_6$$

$$\frac{\partial N_3}{\partial t} = -W_{36} N_3 + W_{63} N_6 + W_{43} N_4 - W_{34} N_3 - \frac{1}{\tau_{R3}} N_3$$

$$+ A_{63} N_6 + A_{53} N_5 + A_{43} N_4 - 2K N_3^{\frac{2}{3}}$$

$$\frac{\partial N_4}{\partial t} = W_{14} N_1 - W_{41} N_4 - W_{34} N_3 + W_{34} N_3 - \frac{1}{\tau_{R4}} N_4$$

$$+ A_{64} N_6 + A_{54} N_5 - W_{CR1} N_1 N_4 + W_{CR2} N_1 N_6$$

$$\frac{\partial N_5}{\partial t} = -\frac{1}{\tau_{R5}} N_5 + A_{65} N_6 + K N_3^{\frac{1}{3}}$$

$$\frac{\partial N_6}{\partial t} = W_{36} N_3 - W_{63} N_6 - \frac{1}{\tau_{R6}} N_6 - W_{CR2} N_1 N_6$$

(1a) (1b) (1c) (1d) (1e) (1f)

where Aij = βij / N0 take into account radiative and non-radiative decays, βij are the branching ratios, τRi are the i-th level lifetimes, K is the ETU rate, and WCR1 and WCR2 are the cross-relaxation transition rates. The condition N1 + N2 + N3 + N4 + N5 + N6 = NHo is considered, where NHo is the dopant concentration. The transition rate Wi,j for the i → j transition is defined as

$$W_{i,j} (z,t) = \frac{\sigma_{i,j} (\lambda_p/\lambda_s)}{\alpha_{p/s}} [P_p (z,t)] i_p/s (x,y)$$

(2)

where σi,j(λp/λs) is the cross section at the wavelength λp/λs for the i → j transition, h is the Plank constant, c0 is the light speed in vacuum, λp/λs is the pump/signal wavelength, Pp is the forward/backward pump power, Ps is the forward/backward signal power, ip and is are the normalized transverse intensity profiles, i.e., the squared modulus of the electromagnetic field, of pump and signal beams, respectively.

The power propagation for pump and signal beams is considered by the following partial differential equations

$$\frac{\partial P_p}{\partial z} + \frac{1}{v_g} \frac{\partial P_p}{\partial t} = [g_p (z,t) - \alpha] P_p (z,t)$$

$$\frac{\partial P_s^\pm}{\partial z} \pm \frac{1}{v_s} \frac{\partial P_s^\pm}{\partial t} =$$

$$= \pm [g_s (z,t) - \alpha] P_s^\pm (z,t) \pm 2h\nu_s B_{\text{crit}} \sigma_{43} n_{4s} (z,t)$$

(3a) (3b)
where
\[ g_p(z,t) = -\sigma_{14}(\nu_p)n_{1p}(z,t) + \sigma_{41}(\nu_p)n_{4p}(z,t) \]
\[ -\sigma_{36}(\nu_p)n_{3p}(z,t) + \sigma_{63}(\nu_p)n_{6p}(z,t), \]
\[ g_s(z,t) = -\sigma_{34}(\nu_s)n_{3s}(z,t) + \sigma_{43}(\nu_s)n_{4s}(z,t), \]
are the gain coefficients for the pump and the signal, respectively. \( \alpha \) is the glass optical loss, \( v_p^0 \) and \( v_s^0 \) are the group velocity for the pump and the signal, respectively, and \( B_{ase} \) is the equivalent noise bandwidth for the Amplified Spontaneous Emission (ASE), \( n_{i,p,s} \) are the overlap integrals over the rare earth-doped region \( \Omega_i \) between the \( i \)-th level population distribution \( N_i(x, y, z, t) \) and the pump/signal optical mode intensity \( i_{p,s}(x, y) \) and they are defined as follows.

\[
\begin{align*}
n_{1p}(z,t) &= \int_{\Omega_d} N_1(x, y, z, t) i_p(x, y) \, dx \, dy \\
n_{3p}(z,t) &= \int_{\Omega_d} N_3(x, y, z, t) i_p(x, y) \, dx \, dy \\
n_{4p}(z,t) &= \int_{\Omega_d} N_4(x, y, z, t) i_p(x, y) \, dx \, dy \\
n_{6p}(z,t) &= \int_{\Omega_d} N_6(x, y, z, t) i_p(x, y) \, dx \, dy \\
n_{3s}(z,t) &= \int_{\Omega_d} N_3(x, y, z, t) i_s(x, y) \, dx \, dy \\
n_{4s}(z,t) &= \int_{\Omega_d} N_4(x, y, z, t) i_s(x, y) \, dx \, dy
\end{align*}
\]

These coefficients allow to take into account the overlapping strength between the spatial distribution of ion populations and the electromagnetic field.

To solve (3), the following initial conditions are imposed.

\[
\begin{align*}
P_p(0,t) &= P_{p0}(t) \\
P_{s+}(0,t) &= R_1P_{s-}(0,t) \\
P_{s-}(0,t) &= R_2P_{s+}(L,t)
\end{align*}
\]

where \( z = 0 \) and \( z = L \) represent the ends of the laser cavity. \( P_{p0}(t) \) is the input pump power, \( R_1 \) and \( R_2 \) are the first and second mirror reflectivity, respectively. Time initial conditions are also considered as follows.

\[
\begin{align*}
N_1(x, y, z, 0) &= N_{1tot}(x, y, z) \\
N_2(x, y, z, 0) &= N_3(x, y, z, 0) = N_4(x, y, z, 0) = N_5(x, y, z, 0) = N_6(x, y, z, 0) = 0 \\
P_p(z, 0) &= P_{s+}(z, 0) = P_{s-}(z, 0) = 0
\end{align*}
\]

To evaluate the time evolution of the generated pulses, the output power is defined as

\[
P_{s\text{out}}(t) = [1 - R_2(\nu_s)]P_{s+}(L,t)
\]

III. PULSED LASER DESIGN

The considered fiber is a step-index double-cladding fluorindate (InF\(_3\)) glass fiber, doped with 10 mol.% of Ho\(^{3+}\) ions, commercially available by Le Verre Fluoré [17]. The core diameter is \( d_{co} = 16 \mu m \) and the numerical aperture \( NA = 0.2 \).

The cladding is 2-D shaped, obtained with circular diameter \( d_{cl1} = 100 \mu m \) truncated by two parallel plans at a distance \( d = 90 \mu m \), to enhance cladding pump absorption. The second cladding has diameter \( d_{cl2} = 155 \mu m \). Fig. 2 illustrates the fiber section geometry and the electric field modulus (V/m), arbitrarily normalized, of the fundamental HE\(_{11}\) mode.
Table I
Spectroscopic Parameters of Fluoroindate Glass Fiber [28], [29]

| Symbol | Value | Description |
|--------|-------|-------------|
| $\sigma_{\Delta}(\lambda_p)$ | $4.3 \times 10^{-20}$ m$^2$ | Absorption cross section $I_6 \rightarrow I_5$ |
| $\sigma_{\Delta}(\lambda_p)$ | $4.3 \times 10^{-20}$ m$^2$ | Emission cross section $I_5 \rightarrow I_6$ |
| $\sigma_{\Delta}(\lambda_p)$ | $7.1 \times 10^{-20}$ m$^2$ | Absorption cross section $I_6 \rightarrow S_2$ |
| $\sigma_{\Delta}(\lambda_p)$ | $7.1 \times 10^{-20}$ m$^2$ | Emission cross section $S_2 \rightarrow I_6$ |
| $\sigma_{\Delta}(\lambda_s)$ | $3.4 \times 10^{-20}$ m$^2$ | Absorption cross section $I_6 \rightarrow I_5$ |
| $\sigma_{\Delta}(\lambda_s)$ | $3.4 \times 10^{-20}$ m$^2$ | Emission cross section $I_5 \rightarrow I_6$ |
| $\tau_{\Delta_2}$ | 16.2 ms | $I_5$ radiative lifetime |
| $\tau_{\Delta_3}$ | 6.2 ms | $I_6$ radiative lifetime |
| $\tau_{\Delta_4}$ | 135 µs | $I_5$ radiative lifetime |
| $\tau_{\Delta_5}$ | 16.3 µs | $F_3$ radiative lifetime |
| $\tau_{\Delta_6}$ | 312 µs | $S_2$ radiative lifetime |
| $\rho_{\Delta_2}$ | 0.942 | $I_6 \rightarrow I_5$ branching ratio |
| $\rho_{\Delta_3}$ | 0.058 | $I_5 \rightarrow I_6$ branching ratio |
| $\rho_{\Delta_4}$ | 0.557 | $I_6 \rightarrow I_5$ branching ratio |
| $\rho_{\Delta_5}$ | 0.430 | $I_5 \rightarrow I_6$ branching ratio |
| $\rho_{\Delta_6}$ | 0.013 | $I_5 \rightarrow I_6$ branching ratio |
| $\rho_{\Delta_5}$ | 0.758 | $F_3 \rightarrow I_5$ branching ratio |
| $\rho_{\Delta_5}$ | 0.192 | $F_3 \rightarrow I_6$ branching ratio |
| $\rho_{\Delta_5}$ | 0.046 | $F_3 \rightarrow I_5$ branching ratio |
| $\rho_{\Delta_5}$ | 0.004 | $S_2 \rightarrow I_6$ branching ratio |
| $\rho_{\Delta_5}$ | 0.500 | $S_2 \rightarrow I_5$ branching ratio |
| $\rho_{\Delta_5}$ | 0.040 | $S_2 \rightarrow I_6$ branching ratio |
| $\rho_{\Delta_5}$ | 0.100 | $S_2 \rightarrow I_5$ branching ratio |
| $\rho_{\Delta_5}$ | $\approx 0$ | $S_2 \rightarrow I_6$ branching ratio |
| $\rho_{\Delta_5}$ | $\approx 0$ | $S_2 \rightarrow F_3$ branching ratio |
| $K$ | $2.11 \times 10^{-24}$ m$^3$/s | Energy transfer upconversion (ETU) rate |
| $W_{\text{CR1}}$ | $3.48 \times 10^{-23}$ m$^3$/s | Cross relaxation (CR1) rate |
| $W_{\text{CR2}}$ | $1.5 \times 10^{-22}$ m$^3$/s | Cross relaxation (CR2) rate |

A. Model Validation

The six-level model is validated by considering the experimental data reported in literature [31]. In particular, Fig. 3 shows the comparison between the six-level model and of the five-level model simulated efficiencies, with respect to the measured values, for a CW input pump, i.e., for a duty cycle $D = 100\%$, fiber length $L_{\text{fiber}} = 23$ cm, and second mirror reflectivity $R_2 = 84\%$ [31]. A slope efficiency $\eta_{\text{CW}} = 8.9\%$ and power threshold $P_{\text{th}} = 4.2$ W are simulated with the six-level model. These values are in good agreement with the experimental ones $\eta_{\text{CW}} = 10.2\%$ and $P_{\text{th}} = 4.3$ W. The five-level model provides less accurate simulation results, the slope efficiency being $\eta_{\text{CW}} = 2.77\%$ and the power threshold $P_{\text{th}} = 1.5$ W with a significant deviation with respect to the experimental values. The discrepancy between the experimental values and the six-level model simulated parameters could be due to i) the employed attenuation $\alpha = 0.2$ dB/m for both pump and signal wavelengths, which is probably overestimated and ii) the employed emission and absorption cross-section approximated as coincident at the two considered wavelengths, listed in Table I. However, in absence of further experimental spectroscopic data, we keep this choice which is precautionary for the laser feasibility investigation.

B. Pulsed Laser Results

As an example of the pulsed laser simulation, Fig. 4 shows the irregular output signal pulses $P_{\text{out}}(t)$ (red curve) at the end of the fiber length $L_{\text{fiber}}$ and the input pump pulses $P_{\text{in}}(t)$ (black curve), with peak power $P_{\text{peak}} = 10$ W, as a function of time $t$; pump repetition rate $f = 100$ kHz, input pump duty cycle $D = 50\%$, fiber length $L_{\text{fiber}} = 10$ cm, and second mirror reflectivity $R_2 = 70\%$. In the simulation, the considered input pump laser is the effectively coupled in the fiber. The laser of Fig. 4 is not optimized. The emission exhibits multiple output peaks with unstable amplitudes.

A deep investigation about the dependence of the laser output signal peak power $P_{\text{peak}}$, output signal pulse width $\tau_s$, and energy $E_s$, on the laser fiber length $L_{\text{fiber}}$ for different pairs of input pump duty cycle $D$ and second mirror reflectivity $R_2$, (see Figs. 5 – 7) is carried out. Since variations of the input pump duty cycle $D$ and of the second mirror reflectivity $R_2$ are strictly related, they have been investigated simultaneously. After a high number of simulations, only the cases of practical interest, with stable single pulse operation, are reported. For all investigated
cases, the output residual pump peak power was under the 1% of the input pump peak power.

Fig. 5 shows the output signal peak power $P^\text{peak}_s$ as a function of the laser fiber length $L_{\text{fiber}}$, for different pairs of input pump duty cycle $D$ and second mirror reflectivity $R_2$; pump repetition rate $f = 100$ kHz. As the input pump duty cycle $D$ increases, the second mirror reflectivity $R_2$ must increase to guarantee single pulse output. This induces a strong decrease of the output signal peak power $P^\text{peak}_s$. The maximum output signal peak power $P^\text{peak}_s = 14.76$ W is obtained for the fiber length $L_{\text{fiber}} = 6$ cm, with input pump duty cycle $D = 25\%$ and second mirror reflectivity $R_2 = 85\%$.

Fig. 6 shows the output signal pulse width $\tau_s$ as a function of the laser fiber length $L_{\text{fiber}}$, for different pairs of input pump duty cycle $D$ and second mirror reflectivity $R_2$; pump repetition rate $f = 100$ kHz. The output pulse width $\tau_s$ increases almost linearly with the fiber length $L_{\text{fiber}}$. It is weakly dependent on the input pump duty cycle $D$ and the second mirror reflectivity $R_2$. To shorten the output optical pulse duration, reduced fiber lengths $L_{\text{fiber}}$ are more suitable. The shortest output pulse width $\tau_s = 58.9$ ns is obtained for input pump duty cycle $D = 25\%$, second mirror reflectivity $R_2 = 85\%$, and fiber length $L_{\text{fiber}} = 5$ cm. This small length value is feasible thanks to the very high dopant concentration.

Fig. 7 shows the output signal pulse energy $E_s$ as a function of the laser fiber length $L_{\text{fiber}}$, for different pairs of input pump duty cycle $D$ and second mirror reflectivity $R_2$; pump repetition rate $f = 100$ kHz. It grows almost linearly with the fiber length $L_{\text{fiber}}$ and it is quite independent from the input pump duty cycle $D$ and the second mirror reflectivity $R_2$. The maximum output signal pulse energy $E_s = 1.37 \mu$J is obtained for the input pump duty cycle $D = 30\%$, second mirror reflectivity $R_2 = 77\%$, and fiber length $L_{\text{fiber}} = 12$ cm, leading to an optical-to-optical internal efficiency $\eta = 4.57\%$. The fiber length $L_{\text{fiber}} = 5$ cm allows the shortest obtained pulse width $\tau_s$ but leads to the minimum output signal pulse energy $E_s$. To find a tradeoff among the output signal peak power $P^\text{peak}_s$ as high as possible, the output signal pulse width $\tau_s$ as short as possible, and the output signal pulse energy $E_s$ as high as possible, the combination $R_2 = 77\%$ and $L_{\text{fiber}} = 8$ cm is chosen for the next investigations.

The investigation is completed by considering the dependence of the laser output signal peak power $P^\text{peak}_s$, output signal pulse width $\tau_s$, and energy $E_s$ on the input pump duty cycle $D$, for different values of the pump repetition rate $f$ (see Figs. 8–10).

Fig. 8 shows the output signal peak power $P^\text{peak}_s$ as a function of the input pump duty cycle $D$, for different values of the pump repetition rate $f$; fiber length $L_{\text{fiber}} = 8$ cm; second mirror reflectivity $R_2 = 77\%$, input pump peak power $P^\text{peak}_p = 10$ W. The domains of correct laser operation are very narrow and strongly discontinuous. For each value of $f$ only a small variation of $D$ is allowed in order to obtain a stable single pulse output. Moreover, as the pump repetition rate $f$ increases, also the input pump duty cycle $D$ must increase to obtain the correct pulsed laser operation with stable single pulse output. The output signal peak power $P^\text{peak}_s$ slightly increases, varying from $P^\text{peak}_s = 14.5$ W to $P^\text{peak}_s = 14.87$ W, as $f$ and $D$ increase.

Fig. 9 shows the output signal pulse width $\tau_s$ as a function of the input pump duty cycle $D$, for different values of the pump
LOCONSOLE et al.: DESIGN OF A GAIN-SWITCHED PULSED LASER AT 3.92 μm WAVELENGTH BASED ON A HO³⁺-DOPED FLUOROINDATE FIBER

Fig. 8. Output signal peak power $P_{\text{peak}}$ as a function of the input pump duty cycle $D$, for different values of the pump repetition rate $f$. Fiber length $L_{\text{fiber}} = 8$ cm, second mirror reflectivity $R_2 = 77\%$.

Fig. 9. Output signal pulse width $\tau_s$ as a function of the input pump duty cycle $D$, for different values of the pump repetition rate $f$. Fiber length $L_{\text{fiber}} = 8$ cm, second mirror reflectivity $R_2 = 77\%$.

Fig. 10. Output signal pulse energy $E_s$ as a function of the input pump duty cycle $D$, for different values of the pump repetition rate $f$. Fiber length $L_{\text{fiber}} = 8$ cm, second mirror reflectivity $R_2 = 77\%$. The output signal pulse width $\tau_s$ slightly decreases by increasing the pump repetition rate $f$ and the input pump duty $D$, changing from $\tau_s = 72.75$ ns to $\tau_s = 71.9$ ns.

Fig. 11. (a) Output signal pulses (red curve) and the input pump pulses (black curve), with peak power $P_{\text{peak}} = 10$ W, as a function of time. Pump repetition rate $f = 100$ kHz, input pump duty cycle $D = 30\%$, fiber length $L = 8$ cm, second mirror reflectivity $R_2 = 77\%$. (b) Zoom of a single output signal pulse.

Fig. 10 shows the output signal pulse energy $E_s$ as a function of the input pump duty cycle $D$, for different values of the pump repetition rate $f$; fiber length $L_{\text{fiber}} = 8$ cm, second mirror reflectivity $R_2 = 77\%$. The output signal pulse energy $E_s$ exhibits a small increment as the pump repetition rate $f$ and the input pump duty $D$ increase. It is $E_s = 1.207 \mu$J for $f = 50$ kHz and $D = 20\%$ and $E_s = 1.23 \mu$J for $f = 200$ kHz and $D = 41\%$. This investigation predicts that good laser performances can be obtained till $f = 200$ kHz also by varying the pump repetition rate in the whole investigated range, promising great flexibility of the proposed device.

Lastly, the output signal pulses $P_{\text{out}}(t)$ (red curve) and the input pump pulses $P_{\text{in}}(t)$ (black curve), with peak power $P_{\text{peak}} = 10$ W, as a function of time $t$, for the optimized cavity is illustrated in Fig. 11 for the pump repetition rate $f = 100$ kHz, duty cycle $D = 30\%$, fiber length $L_{\text{fiber}} = 8$ cm, output mirror reflectivity $R_2 = 77\%$. A stable single pulse signal at $\lambda_s = 3.92$ μm with an output signal peak power $P_{\text{peak}} = 14.62$ W, pulse width $\tau_s = 72.55$ ns, signal pulse energy $E_s = 1.214 \mu$J and optical-to-optical internal efficiency $\eta = 4.05\%$ is obtained. The time to first pulse is $t_{fp} = 15$ μs and the stable gain-switched regime is achieved after about $t_R = 60$ μs. The obtained efficiency is consistent with the CW laser one [31].
These results pave the way to fabricate a new pulsed laser, based on a commercially available fluorindate fiber, with a stable output in a wide range of repetition pump rates \( f \), from \( f = 50 \) kHz to beyond 200 kHz. We underline that, due to the narrow domains in which the laser exhibits stable single pulse operation, the optimized laser parameters, identified in the proposed design, provide useful guidelines to be followed in order to obtain a feasible pulsed emission. The interest is also due to the potential optimizations which could be obtained by co-doping the fluorindate fiber with Ho\(^{3+}\) and Nd\(^{3+}\) ions and employing a pumping scheme at \( \lambda_p = 808 \) nm [38].

IV. CONCLUSION

For the first time, a pulsed laser emitting at \( \lambda_e = 3.92 \) \( \mu \)m based on a commercial double-cladding heavily holmium-doped fluorindate glass fiber is accurately designed via a validated model, by using measured spectroscopic parameters. By employing an input pump with peak power \( P_{\text{peak}} = 10 \) W at the wavelength \( \lambda_p = 888 \) nm, repetition rate \( f = 100 \) kHz and duty cycle \( D = 30\% \), stable output pulses having peak power \( P_{\text{peak}} = 14.62 \) W, pulse width FWHM \( \tau_p = 72.55 \) ns and pulse energy \( E_p = 1.214 \) \( \mu \)J, are simulated. The proposed gain-switched laser enables stable pulsed output in a wide range of pump repetition rates, from \( f = 50 \) kHz to beyond \( f = 200 \) kHz. Future development will include different co-doping and pumping scheme solutions.

REFERENCES

[1] D. D. Hudson, “Short pulse generation in mid-IR fiber lasers,” Opt. Fiber. Technol., vol. 20, no. 6, pp. 631–641, Dec. 2014.
[2] Q. Luo et al., “Remote sensing of pollutants using femtosecond laser pulse fluorescence spectroscopy,” Appl. Phys. B, vol. 82, pp. 105–109, Nov. 2005.
[3] A. Y. Sajjad, K. Mitra, and M. Grace, “Ablation of subsurface tumors using an ultra-short pulse laser,” Opt. Lasers Eng., vol. 49, no. 3, pp. 451–456, Mar. 2011.
[4] L. Romoli, G. Lazzini, A. H. A. Lutey, and F. Fuso, “Influence of ns laser texturing of AISI 316L surfaces for reducing bacterial adhesion,” CIRP Ann., vol. 69, no. 1, pp. 529–532, 2020.
[5] A. E. Klingbeil, I. J. Jeffries, and R. K. Hanson, “Temperature-dependent mid-IR absorption spectra of gaseous hydrocarbons,” J. Quant. Spectrosc. Radiat. Transf., vol. 107, no. 3, pp. 407–420, Oct. 2007.
[6] J. M. Bakker et al., “The mid-IR absorption spectrum of gas-phase clusters of the nucleobases guanine and cytosine,” Phys. Chem. Chem. Phys., vol. 6, no. 10, pp. 2810–2815, Apr. 2004.
[7] K. Wang, D.-W. Sun, and H. Pu, “Emerging non-destructive terahertz spectroscopic imaging technique: Principle and applications in the agri-food industry,” Trends Food Sci. Technol., vol. 67, pp. 93–105, Sep. 2017.
[8] M. C. Falconi, D. Laneve, M. Boffetti, T. T. Fernandez, G. Galenzano, and F. Prudenzo, “Design of an efficient pulsed Dy\(^{3+}\)-: ZBLAN fiber laser operating in gain switching regime,” J. Lumin. Technol., vol. 36, no. 23, pp. 5327–5333, Sep. 2018.
[9] X. Jin et al., “High-power ultralong-wavelength Tm-doped silica fiber laser cladding-pumped with a random distributed feedback fiber laser,” Sci. Rep., vol. 6, Jul. 2016, Art. no. 20052.
[10] E. A. Anashkina, “Laser sources based on rare-earth ion doped tellurite glass fibers and microfibers,” Fibers, vol. 8, no. 3, pp. 1–17, May 2020.
[11] M. C. Falconi et al., “Dysprosium-doped chalcogenide master oscillator power amplifier (MOPA) for mid-IR applications,” J. Lumin. Technol., vol. 35, no. 2, pp. 265–273, Jan. 2017.
[12] M. R. Majewski, R. I. Woodward, J.-Y. Carrée, S. Poulain, M. Poulain, and S. D. Jackson, “Emission beyond \( 4 \) \( \mu \)m and mid-infrared lasing in a dysprosium-doped indium fluoride (InF\(_3\)) fiber,” Opt. Lett., vol. 43, no. 8, pp. 1926–1929, 2018.
Antonella Maria Loconsole received the M.Sc. degree in 2019 in telecommunications engineering (cum laude) from Politecnico di Bari, Bari, Italy, where she is currently working toward the Ph.D. degree in electrical and information engineering. Her research interests include SIW antennas, microwave applicators for medical applications, and optical fiber lasers and amplifiers.

Mario Christian Falconi received the M.Sc. degree in electronic engineering (cum laude) and the Ph.D. degree in electrical and information engineering from Politecnico di Bari, Bari, Italy, in 2015 and 2019, respectively. In 2019, he was a Research Fellow and is currently a Research Assistant in electromagnetic fields with the Department of Electrical and Information Engineering, Polytechnic University of Bari, Bari, Italy. His research interests include fiber lasers and amplifiers, photonic crystal fibers, and nonlinear effects in optical fibers.

Vincenza Portosi received the M.Sc. degree in 2018 in electronic engineering (cum laude) from Politecnico di Bari, Bari, Italy, where she is currently working toward the Ph.D. degree in electrical and information engineering. Her research interests include microwave applicators for medical applications, metamaterials, SIW antennas, and optical fiber sensors.

Francesco Prudenzano (Member, IEEE) received the Ph.D. degree in electronic engineering from Politecnico di Bari, Bari, Italy, in November 1996. Since 2018, he has been a Full Professor in electromagnetic fields with the Department of Electrical and Information Engineering, Politecnico di Bari, Bari, Italy. His research interests include the design and characterization of microwave devices, integrated optics, and optical fiber-based devices. He is currently the Head of Microwave and Optical Engineering Group, Department of Electrical and Information Engineering, Politecnico di Bari. From 2017 to 2018, he was the Chair of SIOF, the Italian Society of Optics and Photonics (Italian branch of EOS - European Optical Society). He is involved in several national and international research projects and cooperations. He has coauthored more than 400 publications, 295 of which got published in journals and international conferences, lectures, and invited papers.