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A New Ultrafast and High Peak Power Fiber Laser operating at 1.5 µm using InN as Saturable Absorber

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Abstract: This work describes a novel ultrafast (<250 fs) fiber laser operating at 1.5 µm and based on InN as saturable absorber (SA). This SA accommodates much higher fluencies than comparable semiconductor or graphene-based SAs.

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1. Introduction

High power radiation sources at 1.5 µm have been lately studied in depth since they find application in several fields, as for example research, medicine or telecommunications [1]. Recently, ultrafast fiber lasers have attracted much attention due not only to their simplicity of fabrication and compactness, but also to their capability to achieve extremely short pulses, enormous peak power, and a wide range of operation wavelengths. Passive mode-locking using a saturable absorber is a common technique used to achieve ultrashort pulses with high peak power. Materials like graphene [2], carbon nanotubes [3] or InGaAs/GaAsSb [4] have been proposed as saturable absorbers at 1.5 µm. InN is an interesting and unexplored alternative. Its direct band gap (0.65 – 0-85 eV), enhanced optical nonlinearity and high thermal and chemical stability make it a suitable candidate for the development of saturable absorbers in the near-infrared spectral range.

In this work, we present and characterize a new ultrafast mode-locked fiber laser which consists of a ring resonator incorporating an InN layer working as saturable absorber. The laser emits very stable soliton-type pulses with duration of less than 250 fs and peak power in the order of 10 kW, spectrally centered at 1.5 µm, and with tunable repetition rate (from 0.4 to 4 MHz).

In order to maximize the peak power, two different options have been explored, namely the insertion of additional fiber to reduce the repetition rate, and the use of a master oscillator power amplifier (MOPA) configuration [5, 6]. The former approach resulted in a 5-fold increase of the peak power, whereas the latter led to pulses with peak power above 1 MW and pulse widths as low as 55 fs.

2. InN characterization and laser design

The saturable absorber consists on a 1 µm-thick InN layer grown on 10-µm-thick GaN-on-sapphire template by molecular beam epitaxy [7]. Figure 1(a) presents the nonlinear change in transmittance as a function of the incident fluence at 1.5 µm, measured with a pulsed laser (pulse duration = 200 fs, maximum average power = 30 mW). The results are well fitted using available models of saturable absorption in semiconductors [8]. In the studied pump power range, a nearly 100% change in transmittance can be observed. A linear transmittance of T_{lin}=28% and non-

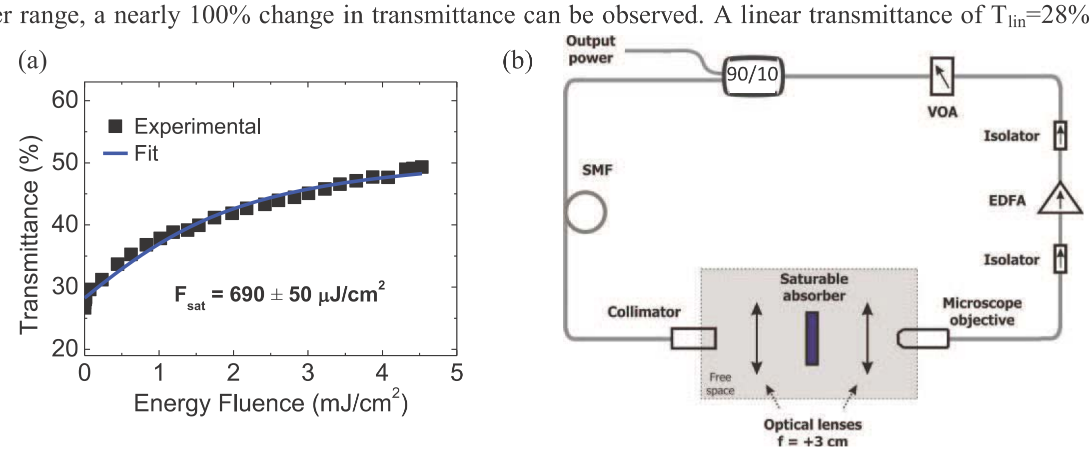

Figure 1: (a) Variation of the transmittance the InN layer as a function of the energy fluence at 1.5 µm. (b) Configuration of the mode-locked fiber laser resonator.

saturable transmittance of T_{ns}=53% have been estimated from the fitting. It is important to note that the fluencies reached are high enough to reach optical damage in most of the known SAs working at 1.5 µm. In the case of InN, however, fluencies up to 5 mJ/cm^2 did not cause any damage in the response of the device

The InN saturable absorber is placed in a free space section, between two achromatic-lenses with 3-cm focal length, within a ring laser resonator of single mode optical fiber (Fig. 1(b)). A typical Er-doped fiber amplifier (EDFA) is used as the gain medium. An optical fiber attenuator (VOA) allows controlling the average power inside the laser cavity. The 10% of the power cavity is led to the output of the laser though a 90/10 fiber coupler. The configuration has a total length of 41 m, which represents a repetition rate of 4.8 MHz. The laser has proved to be self-starting. Furthermore, no polarization dependence is observed within the cavity. This is because InN saturable absorber is placed so that its <0001> crystallographic axis is aligned with the laser cavity. In such a configuration, the optical asymmetry within the basal plane of InN is too small to induce remarkable changes with polarization of the incident light, in contrast with Kerr-lens or saturable absorbers based on nonlinear polarization rotation.

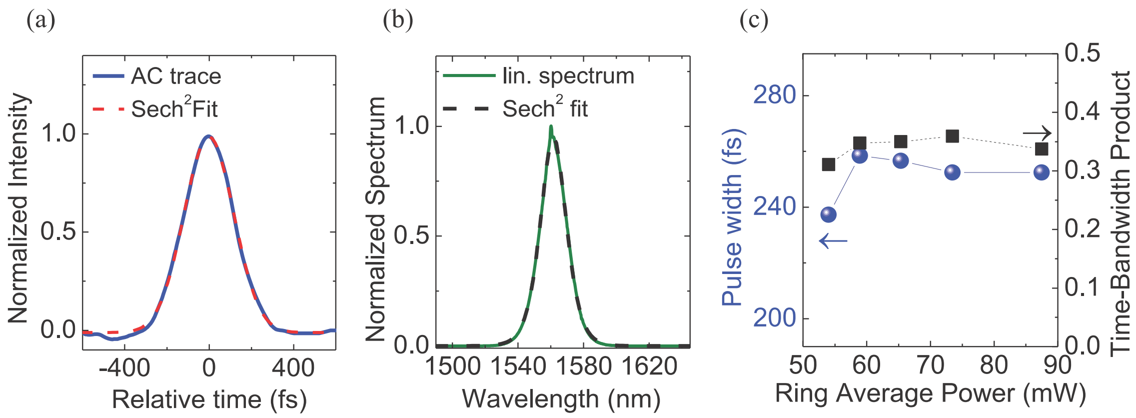

Figure 2: Laser output presenting (a) autocorrelation trace and (b) spectrum with fitting to a sech^2 function, and (c) variation of pulse width and time-bandwidth product as a function of the average power within the laser resonator.

3. Laser characterization

The laser (depicted in Fig. 1(b)) emits a very stable train of pulses with a full width at half maximum (FWHM) time duration of 250 fs (Fig. 2(a)). The pulses are centered at a wavelength of 1.56 µm and present a spectral width of 16 nm (Fig. 2(b)). The obtained time-bandwidth product (TBP) presented in Fig. 2(c) confirms that the pulses are almost transform-limited (Fig. 2(c)), which is characteristic of soliton pulses. The peak power and pulse energy of the pulses are 8 kW and 2 nJ, respectively, corresponding to an average power of 10 mW.

For the maximization of the pulse peak power, fiber reels with different lengths have been connected to the resonator. For fiber reels up to 200 m, the repetition rate of the laser has been reduced, while maintaining the average power, pulse duration and TBP without major changes. The addition of fiber to the laser resonator introduces a change in average dispersion of the laser cavity, which might compensate the increase in pulse energy, thus maintaining the pulse duration relatively stable (see Table 1). Therefore, both peak power and pulse energy increase by a factor of 5. On the other hand, when placing fiber reels with lengths > 300 meters, more than 1 pulse is observed inside the cavity. As an example, when inserting a 1 km reel, the measured repetition rate is 0.37 kHz, double than the theoretically expected value from the total length of fiber in the resonator. This confirms that 2 pulses are simultaneously circulating along the cavity. This could be explained since considering that the pulse energy increases with the cavity length . Beyond a pulse energy threshold, the saturable absorber might not be

Additional Fiber Length	0 m	30 m	45 m	200 m	1000 m
Average Power (mW)	9.7	9.7	9.7	9.6	9.6
Rep. Freq. (MHz)	4.84	3.54	2.84	0.84	0.37
Pulse duration (fs)	253	265	274	277	----
Peak power (kW)	7.9	10.3	12.5	25.7	----
TBP	0.34	0.38	0.36	0.36	----

Table 1: Experimental characterization results obtained when increasing the fiber length in the laser resonator.

completely relaxed after the pulse generation, leading to an increase of the probability of developing a second pulse generation from the residual optical noise in the cavity within a round trip time. .

On the other hand, we have studied the laser performance under MOPA configuration. For this purpose, a second amplifier has been placed at the output of the aster oscillator. It has been observed that beyond a certain value of amplification (with average powers above 360 mW), thepulses break into side-lobes due to the onset of self-phase modulation within the amplifier. We have acquired the autocorrelation and power spectra of the laser up to the limit in which, we can consider that we still have good quality pulses (360 mW). Fig. 3 shows the autocorrelation traces and spectra measured for different average power. The presence of side-lobes is clearly appreciated in Fig. 3(a). However, considering that all the power is in the central peak, and from the fitting to a $sech^2$ function we found pulses with just ~53 fs duration. The spectra show that the peak wavelength is shifted to higher wavelengths (1575 nm) due to Raman self-frequency shift in the second amplifier. The highest recorded peak power is 1.4 MW, corresponding to an average power of 358 mW. This is the highest value ever achieved in a fiber laser mode-locked by a semiconductor SA at 1.5 μm, to the best of our knowledge.

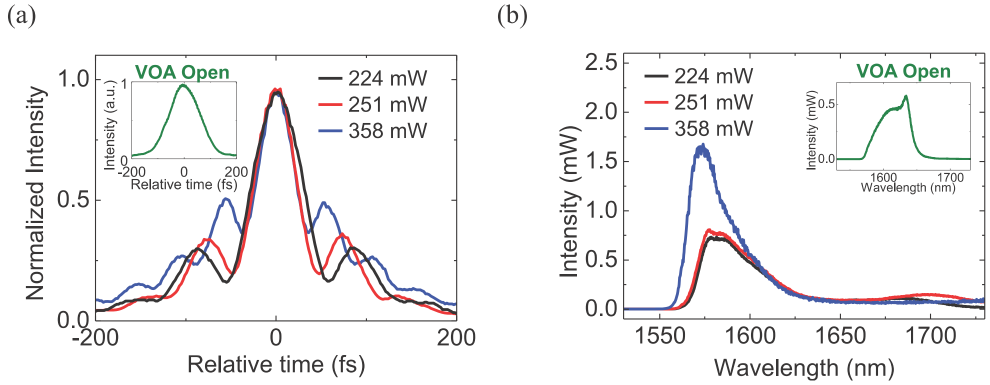

Figure 3: Experimental measurements for MOPA configuration presenting (a) autocorrelation traces and (b) spectra. The insets show the particular case when the VOA is open (minimum attenuation).

4. Conclusions

A new ultrafast polarization-independent fiber laser operating at 1.5 μm has been presented. The novelty of the laser resides on the use of InN as saturable absorber for passive mode-locking. This material exhibits high optical nonlinearities and supports extremely large fluences without optical damage. Due to the semiconductor crystal symmetry, the laser is polarization-independent. The pulses have a FWHM of 250 fs and a peak power of 8 kW, and are spectrally centered at 1.56 μm. Two possibilities to enhance the pulse peak power have been explored. On the one hand, the insertion of additional fiber leads to a 5-fold increase of the peak power, since the repetition rate is reduced while maintaining the pulse properties barely unchanged. On the other hand, in a MOPA configuration, the laser can deliver pulses with FWHM of 53 fs and average power of 360 mW, leading to peak powers in the order of 1.4 MW.

From its relatively easy and cheap configuration, amazing properties and good stability, this new laser could represent a good alternative for the other known and commercial lasers present at the moment.

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