# Sub-250 fs, 650 kW Peak Power Harmonic Mode-Locked Fiber Laser with InN-based SESAM

F. Gallazzi[(1)], M. Jimenez-Rodriguez[(2)], E. Monroy[(3,4)], P. Corredera[(1)], M. González-Herráez[(2)], F. B. Naranjo[(2)], J. D. Ania-Castañón[(1)]

[(1)] Instituto de Óptica “Daza de Valdés”, IO-CSIC, C/Serrano 121, 28006, Madrid, Spain, francesca.gallazzi@io.cfmac.csic.es
[(2)] Photonics Engineering Group, Electronics Dept (EPS), Alcalá University, 28871, Alcalá de Henares, Madrid, Spain
[(3)] University Grenoble-Alpes, 38000 Grenoble, France
[(4)] CEA-Grenoble, INAC-PHELIQS, 17 av. des Martyrs 38000 Grenoble, France

**Abstract** *We demonstrate ultrafast harmonically mode-locked fiber lasing in up to 6-km-long rings at 1.56µm with InN SESAM. Fundamental mode-locking with pulse width of 239fs, pulse energy of 155nJ and peak power of 650kW is achieved with a 1-km-long cavity.*

## Introduction

Recent years have seen an increasing demand for ultrafast radiation sources, owing to their wide variety of applications, from telecommunications to metrological, industrial or biomedical applications. Among the different solutions available, fiber-based passively mode-locked sources relying on saturable absorbers [1] (e.g. InGaAs, GaAsSb) are particularly interesting thanks to their simple implementation and relatively low cost. However, in comparison to other approaches, they deliver relatively low peak power (up to a few kW), which limits their introduction in some application domains. Increasing the length of the resonator is a direct way to increase pulse energy, but this happens at the expense of the temporal width, which typically increases to the ns range[2].

The utilisation of InN as a new saturable absorber was first studied in[3,4], where it was successfully employed to set-up an ultrafast passively mode-locked fiber laser at 1.56 µm, thus with an operation wavelength in the telecommunication window in the same band of traditional Erbium-doped fiber amplifiers (EDFA). Following these results, we recently presented the first demonstration of sub-250 fs pulse generation in a self-starting, highly stable passively mode-locked fiber laser with InN-based semiconductor saturable absorber mirror (SESAM) without the need for polarization control inside the cavity[4].

Here, we show how cavity length in such a laser can be successfully scaled without loss of stability achieving high-energy output pulses (155 nJ) with peak powers of 650.5 kW, while still retaining pulse durations of 239 fs. The system presented combines all the advantages of traditional ultrafast fiber lasers while overcoming its power limitation.

Furthermore, by studying the dynamics of the system as a function of gain and cavity length, we demonstrate the possibility of generating multiple harmonics with high peak power and faster repetition rates.

## Experimental set-up

The fiber laser is implemented as a ring resonator, as depicted in Fig. 1. The saturable absorber (SA) is located inside the ring in free space, with the beam collimated on the material by an achromatic lens. This section is connected with the cavity by an optical circulator. A standard commercial EDFA, delivering a maximum optical power of +24 dBm, is used as gain medium and an isolator guarantees unidirectional propagation in the cavity. Through a fiber coupler, 70% of the radiation is recirculated into the ring, while 30% goes to the laser output. The basic ring is completed by a fiber span, located in between the SESAM and the EDFA, as well as a variable optical attenuator (VOA) located before the EDFA. Two different lengths (1 km and 2.3 km) of standard single mode fiber (SMF) have been tested.

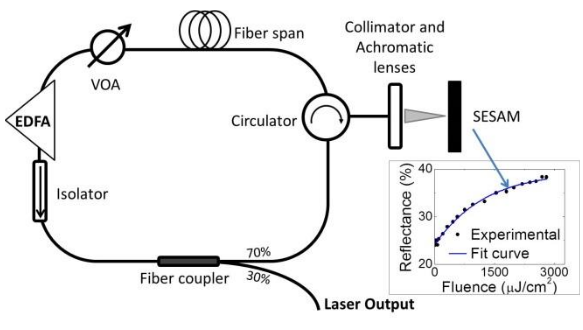


**Fig. 1:** Set-up of the fiber laser. Inset: SESAM nonlinear reflectance measured as a function of fluence.

Note that no polarization control is introduced in the system[3]. The saturable absorber is configured as a reflector. It consists of InN grown by molecular beam epitaxy[4] on a GaN-on-sapphire template, with an Al mirror deposited by RF-sputtering on the InN surface. The properties of this material as a SA have been presented in[3-5] and are confirmed here, being particularly relevant its tolerance to extremely high fluences (>1 TW/cm$^2$) and its insensitivity to the polarization, which results from the alignment of its <0001> crystallographic axis with the laser cavity, which minimizes the optical anisotropy. The reflectance of the SESAM structure is presented as an inset in Fig. 1.

As shown in[4], the basic ring configuration without the SMF extension can achieve stable mode-locking with sub-250 fs pulses.

## Results and discussion

Autocorrelation traces, optical spectra and RF spectra are recorded for each configuration at the laser output. In all situations, once mode-locking is achieved, the self-starting pulse train is very stable and centered at 1.56 µm.

The cavity has been tested with two different lengths of similar SMF fiber, which can be considered to have similar attenuation at 1.55 µm around 0.2 dB/km, as well as similar chromatic and polarization-mode dispersion characteristics, with the zero-dispersion wavelength point far from the operating wavelength of the laser.

In order to confirm the polarization independence of the much longer cavity set-up, we have monitored polarization at the output trough a polarimeter. The measured degree of polarization (DOP) at the output is between 10% and 15%, similar to that obtained for the basic short-cavity configuration.

With a 1 km span introduced in the cavity, it is possible to achieve locking to the fundamental mode, by simply adjusting the VOA to increase cavity losses. As shown in Fig. 2(b), the resultant pulses at fundamental mode-locking are similar in shape to those obtained in the basic ring configuration, with a temporal width at FWHM of $\Delta\tau \approx 239$ fs and spectral width at FWHM of $\Delta\lambda \approx 25.4$ nm. The fundamental repetition rate is measured in 196.4 kHz, corresponding exactly to the cavity length roundtrip, and the average power is P = 30.5 mW. For the 1 km case locked to the fundamental mode, it is possible to achieve stable generation with all the energy contained within the symmetric, Gaussian pulse spectrum, and no significant contribution of EDFA-generated ASE that would contribute to the inter-pulse continuous white noise component, as can be seen from the Gaussian fit of the spectrum in Fig. 2(b).

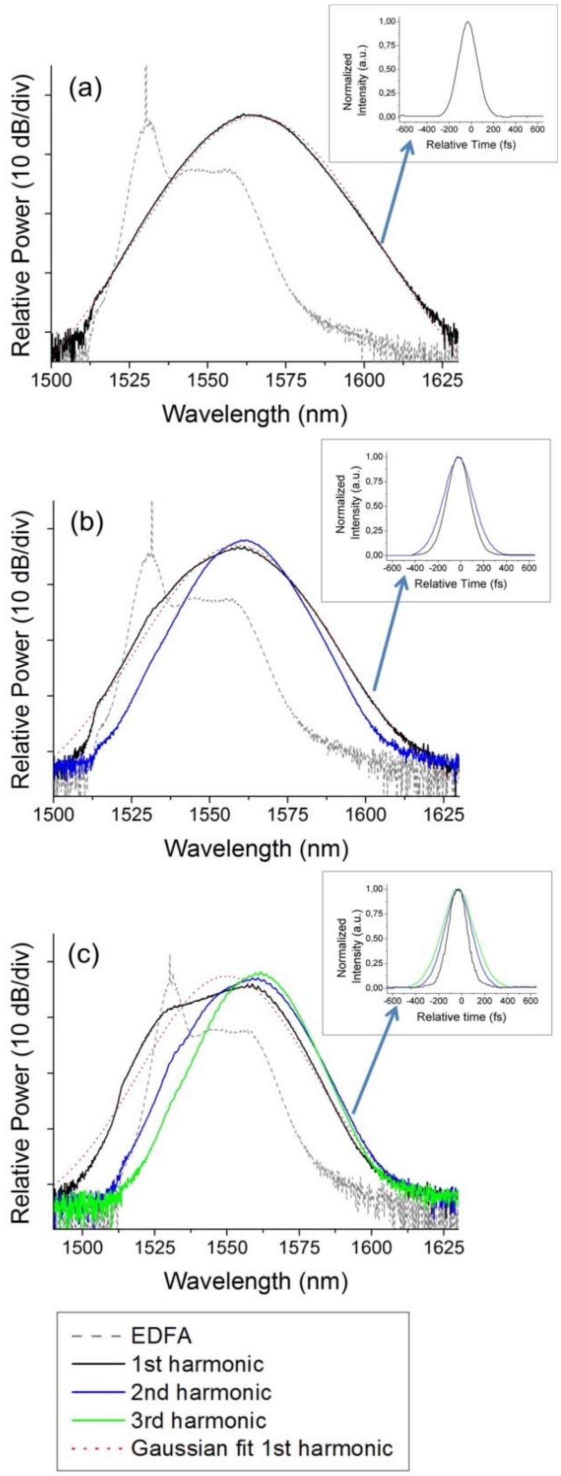


**Fig. 2:** Optical spectra of the laser output under different regimes for (a) the basic configuration, with no additional fiber span, (b) the 1 km configuration and (c) the 2.3 km configuration. The gain spectrum of the EDFA is also included for reference as a discontinuous line. Gaussian fits are provided as dotted line for the spectra of the fundamental harmonic in the three configurations. Inset: corresponding autocorrelation traces.

The resulting pulses display an average power of P = 30.5 mW, a high peak power of $P_p$ = 650,5 kW and pulse energy of $E_p$ = 155.3 nJ. Adjusting the VOA to reduce losses in the cavity it is possible to go through a noisy transition regime, eventually leading to stable, noiseless mode-locking at the second harmonic with longer pulses ($\Delta\tau \approx 313$ fs) of half the energy and peak power around 270 kW.

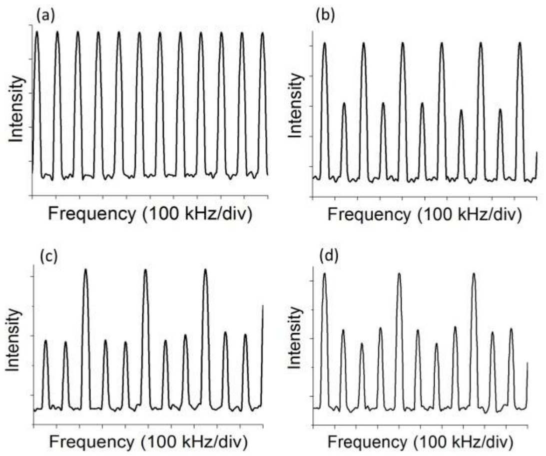


**Fig. 3:** RF spectra of the laser output with 2.3 km of SMF fiber. Repetition frequency of fundamental mode-locking (a), 2nd harmonic (b), 3rd harmonic (c), 4th harmonic (d).

Harmonic mode-locking is easily obtained also with the 2.3 km-long SMF fiber. Here the pulses are consistently locked to a repetition rate of 87 kHz. The measured temporal width is $\Delta\tau \approx 190$ fs, correspondent to a spectral width of $\Delta\lambda \approx 32$ nm. In this case, and although mode-locking is clearly visible in the RF spectrum -see Fig. 4(a)- the optical spectrum -see Fig. 3(c)- deviates from the Gaussian profile, showing instead an important noise contribution following the EDFA gain profile characteristic of the amplifier-generated ASE, which means that an important percentage of the power is contained in the noise component and not just in the pulse.

Adjusting the intensity on the SESAM to achieve mode-locking to higher harmonics leads to noiseless, narrower, symmetric Gaussian spectra. With the 2.3 km-long cavity, stable mode-locking is achieved for all harmonics up to the 5th, which displays pulses with $\Delta\tau \approx 355$ fs, and spectral width $\Delta\lambda \approx 17$ nm.

Given the excellent stability of the system, we tried to further increase ring length, observing stable harmonic mode-locking with cavities of up to 6 km. Although fundamental mode locking does not seem possible with the current configuration and fiber choice beyond 3 km, pulses are still visible and easily stabilized to higher harmonic orders, allowing a broad choice of high peak powers and repetition rates.

## Conclusions

We have demonstrated experimentally for the first time to our knowledge the possibility of achieving, by means of a simple and low-cost set-up, high-power, polarization-independent, passive ultrafast harmonic mode-locking in an optical fiber ring laser operating at 1.56 µm with pulse durations of a few hundreds of fs and peak powers in the order of hundreds of kW. The use of an InN-based SESAM, in combination with a standard 1 km-long SMF cavity and an EDFA allows the generation of 239 fs Gaussian pulses with a repetition rate of 196.4 kHz and a peak power of 650.5 kW, the highest achieved to date, to our knowledge, in a passively mode-locked fiber laser, overcoming what has traditionally been considered one of the main limitations of these kind of systems.

## Acknowledgements

This work was funded by FP7 ITN programme ICONE (608099); Spanish MINECO grant TEC2015-71127-C2, TEC2015-71127-C2-2-R and TEC2012-37958-C02-01; Comunidad de Madrid grant SINFOTON (S2013/MIT-2790-SINFOTON-CM).

## References

[1] J. Koo et al., “Femtosecond harmonic mode-locking of a fiber laser at 3.27 GHz using a bulk-like, MoSe2-based saturable absorber”, Opt. Express, Vol. 24, no. 10, p. 10575 (2016).

[2] J. L. Dong et al., “Sub-100 kHz repetition rate erbium-doped fiber laser in anomalous dispersion regime”, Laser Physics, Vol. 21, no. 6, p. 1111 (2011).

[3] F. B. Naranjo et al., “Nonlinear absorption of InN/InGaN multiple-quantum-well structures at optical telecommunication wavelengths,” Appl. Phys. Lett., Vol. 98, no. 3, p. 031902 (2011).

[4] M. Jimenez-Rodriguez et al., "Widely power-tunable polarization-independent ultrafast mode-locked fiber laser using bulk InN as saturable absorber," Opt. Express, Vol. 25, no. 5, p. 5366 (2017).

[5] M. Jimenez-Rodriguez et al., “Sub-200 fs Mode-Locked Fiber Laser with InN-based SESAM”, accepted to CLEO Europe - EQEC 2017.