Hybrid Mode Locked Fiber Laser Using a PDMS/SWCNT Composite Operating at 4 GHz

Ivan Hernandez-Romano, J. Davila-Rodriguez, Dimitrios Mandridis, Jose. J. Sanchez-Mondragon, Daniel A. May-Arrioja, and Peter J. Delfyett, *Fellow, IEEE*

***Abstract*—A hybrid mode-locked Erbium-doped fiber laser that provides very short pulse-widths while achieving high repetition rates is proposed and experimentally demonstrated. This hybrid configuration is realized by using a thin film of polydimethylsiloxane (PDMS) doped with single wall carbon nanotubes (SWCNT). This PDMS/SWCNT composite acts as a saturable absorber and is inserted within an active mode-locked laser system using angled connectors. Therefore, the effect of the PDMS/SWCNT composite is to effectively narrow the width of the pulses generated by the active system without modifying its repetition rate. A pulse-width of 730 fs was generated at a repetition rate of 4 GHz, while achieving an average output power of 4 mW. A reduction in the noise of the photodetected RF spectrum was also observed in the hybrid system.**

***Index Terms*—Carbon nanotubes, fiber lasers, mode-locked lasers, saturable absorber.**

I. Introduction

Compact sources of ultrashort pulses with high-repetition-rates are highly desirable for a wide range of applications such as optical communication, metrology systems, and optical clocks. When dealing with ultrashort pulses, passive mode-locking is the preferred mechanism since it favors the generation of the shortest pulses. Over the years different passive mode-locking techniques have been demonstrated, such as nonlinear polarization rotation [1] and semiconductor saturable absorber mirror [2]. Recently, passive mode-locking of Erbium-doped fiber lasers (EDFL) using Single Wall Carbon Nanotubes (SWCNTs) as saturable absorbers (SA) have attracted a lot of attention because they generate pulses whose duration can be on the order of one picosecond or less. Among the optical properties of SWCNTs that make them a good SA are their optical nonlinearity [3], ultrafast recovery time [4], and high damage threshold [5], which are the crucial specifications for SAs. In the last five years, different approaches have been used in order to incorporate SWCNTs in an all-fiber laser cavity, and we have reached the point where their integration in fiber laser systems is relative simple [6]–[9]. However, the main drawback of all the lasers presented is the low repetition rate. An obvious approach is of course to make the cavity as short as possible [10], [11], but a small cavity length presents challenges that might increase the system complexity. On the other hand active mode-locked lasers, and in particular harmonic mode-locked laser systems, can generate very high repetition rates by simply incorporating a high speed modulator within the cavity. The key issue in active mode-locking is that they generate pulses whose duration is longer than those of passively mode-locked lasers, especially when etalons are added to stabilize the supermode order [12]. The question remains on how to implement a simple and reliable all-fiber laser with a high repetition rate while generating very short pulses.

Here we propose to implement a hybrid mode-locked Erbium fiber laser that incorporates active mode-locking combined with a SWCNT thin film SA. Such a system will basically bring the best of both worlds, providing a high repetition rate while retaining very short pulses. The active mode-locked system was built using a standard ring cavity laser incorporating an electro-optical modulator. The SA is a thin film of polydimethylsiloxane (PDMS) doped with SWCNT (PDMS/SWCNT) which is inserted within the cavity by placing it between two FC/APC connectors. The PDMS/SWCNT composite effectively reduces the pulsewidth of the system by fifty percent as compared to pure active mode-locking, while generating a pulse train with a repetition rate of 4 GHz with a pulsewidth of 730 fs and an average power of 4 mW.

II. PDMS/SWCNT Thin Film

The diameter of the SWCNTs was chosen between 0.8 to 1.2 nm since they correspond to a bandgap of approximately 1550 nm. The SWCNTs were provided by Unidym and they were synthesized by high-pressure CO (HiPCO) method. A critical issue when mixing carbon nanotubes with a polymer is to achieve a well dispersed solution. The formation of bundles of SWCNTs in the polymer matrix is detrimental for the nonlinear optical absorption, which is the fundamental phenomenon to create a saturable absorber device [13]. In order to fully disperse the SWCNTs, rather than mixing the nanotubes directly in the polymer, we first disperse them in the polymer solvent. Since the solvent for PDMS is chloroform, the SWCNTs were dispersed in chloroform and the suspension was sonicated during 30 minutes. The concentration of SWCNTs was selected at 0.125 wt% since it has been previously shown that this is an

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I. Hernandez-Romano and J. J. Sanchez-Mondragom are with Departamento de Óptica, Instituto Nacional de Astrofísica, Óptica y Electrónica, 72000 Tonantzintla, Puebla, México (e-mail: heriromano@gmail.com; delta_dirac@hotmail.com).

J. Davila-Rodriguez, D. Mandridis, and P. J. Delfyett are with the CREOL & FPCE, The College of Optics and Photonics, University of Central Florida, Orlando, FL 32826 USA (e-mail: josue@creol.ucf.edu; dmandrid@creol.ucf.edu; delfyett@creol.ucf.edu).

D. A. Arrioja-May is with Departamento de Ingeniería Electrónica, UAM Reynosa Rodhe, Universidad Autónoma de Tamaulipas, 88779 Reynosa, Tamaulipas, México (e-mail: daniel_may_arrioja@hotmail.com).

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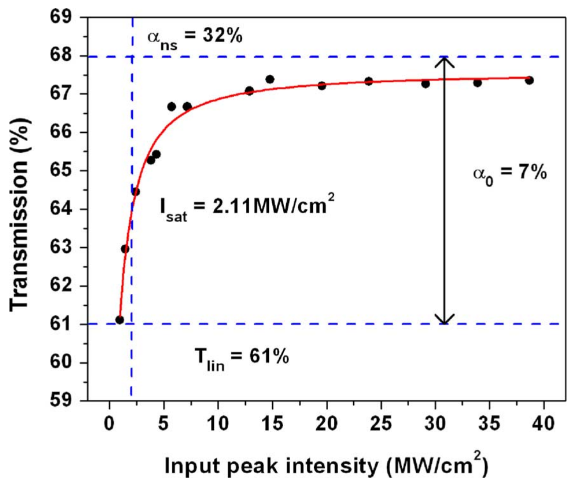

Fig. 1. Transmission characteristics as a function of peak intensity of the PDMS/SWCNT film at 1550 nm.

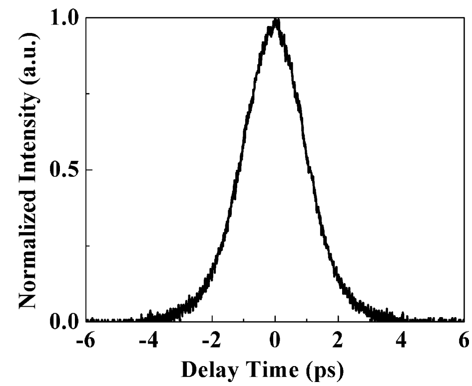

Fig. 2. Autocorrelation trace from the passive mode-locked system.

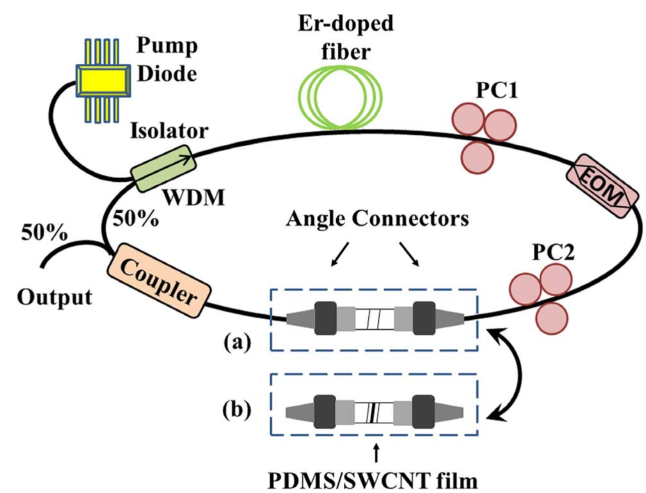

Fig. 3. (a) Schematic of the active mode-locked fiber laser. (b) Schematic of the hybrid mode-locked fiber laser. EOM: electro-optical modulator; WDM: wavelength division multiplexer; Pol. Con.: Polarization Controller.

adequate amount to observe stabilized short pulses [14]. After the nanotubes are fully dispersed, PDMS was slowly added to the solvent while the new mixture was placed in the ultrasonic bath and on the stirring machine for 2 hours and 3 hours, respectively. Twenty percent of the solution weight is chloroform and eighty percent of the solution weight is PDMS. After that, we add ten percent of the total solution weight of the curing agent for the PDMS. Curing of the PDMS is obtained by an organometallic cross-linking reaction to give an optically transparent polymer.

The fabrication process of PDMS/SWCNT film is as follows. Two acrylic layers were used to fabricate a cell whose thickness depends on the spacers between them. Acrylic material is used instead of any other material because PDMS doped with SWCNTs does not stick to it. The PDMS/SWCNT solution was poured into the cell and it was cured by heating up the sample at 95°C for one hour and then we let it rest for 24 hours. After this process the cell can be separated and the resulting film is equal to the thickness of the spacer, with very smooth surfaces. Using this method, the thickness of PDMS/SWCNT films can be controlled accurately by simply changing the thickness of the spacers. The thickness of the film used here was 192 μm. After the film is released a simple experimental setup was implemented to determine the nonlinear transmission properties of the film. This setup consists of a commercial fiber laser with a repetition rate of 250 MHz and a pulsewidth of 150 fs whose intensity is controlled using an optical fiber variable attenuator. After the attenuator the pulses are sent to a coupler (10:90), and 10% of the light was detected by a power meter (it was used to evaluate the input power) while the remaining 90% passed through our sample and then it was sent to another power meter to measure the output power. A polarization controller is used before light reaches the sample, since the PDMS/SWCNT exhibits slight polarization dependence as a result of the random orientation of the embedded SWCNTs. A small piece of the film (2 mm $\times$ 2 mm) was cut and placed between two FC/APC connectors in order to have an all-fiber saturable absorber device. As shown in Fig. 1, the linear transmission of the film is 61% measured at a wavelength of 1550 nm, with nonsaturable losses of 32%. As the intensity of the pulsed laser is incremented, a saturation intensity of 2.11 MW/cm^2 with a modulation depth of 7% is obtained. This modulation depth should be good enough to use this composite for mode-locking applications.

III. Passive Mode-Locked Operation

In order to evaluate the composite film as a mode-locker, the composite with the FC/APC is inserted in a standard EDF ring cavity laser similar to the one shown in Fig. 3, without the modulator and the polarization controller 2. The characteristics of each component in the cavity are explained in detail in the next section. In this cavity, as the pumping power is being increased, a stable pulse train is obtained with a pump power ranging from 31 to 115 mW, with the pulse-width duration being reduced as the pump power is increased. The minimum pulse-width duration was obtained with a pump power of 85 mW. The optical spectrum of the laser reveals a peak wavelength of 1565.3 nm, with a spectral width at FWHM of 2 nm. The temporal width of the autocorrelation trace was 2.23 ps, as shown in Fig. 2, which corresponds to a pulsewidth of 1.26 ps assuming a sech^2 pulse. This corresponds to a time-bandwidth product (TBP) of 0.318, which is close enough to transform-limited sech square pulses [15]. We should also note that the laser could be operated at our maximum pump power of 115 mW, but not significant improvement in terms of the pulsewidth is observed.

With the laser operating at 85 mW a stable mode-locked pulse train of 22.73 MHz was observed with a maximum output power of 4.89 mW. This repetition rate corresponds to the laser cavity length of 8.8 m, and this is the main limitation of passive mode-locked systems. Since their repetition rate is related to the cavity length, in order to increase the repetition rate we need to make a very short laser cavity. This has been attempted in some works but the fabrication of the laser cavity becomes very difficult. As we will show in the next section, a simpler way to achieve high repetition rate while retaining very short pulses is by using a hybrid mode-locked system.

IV. Hybrid Mode-Locked Laser

The hybrid system that we propose here is a combination of an active mode-locked laser and a PDMS/SWCNT film mode locker. The former provides operation at high repetition rates and the latter effectively reduce the width of the pulses. Prior to assembling the hybrid configuration, we decided to test the active mode-locked system in order to better observe the impact of the hybrid configuration. The simplest way to implement an active mode-locked laser is by placing an electro-optical modulator (EOM) inside a ring cavity resonator. The modulator is driven at a modulation frequency that exactly matches a multiple of the fundamental frequency of the laser cavity, which is the inverse of the cavity round-trip time. When the modulator is driven at a multiple of this frequency it is referred to as harmonic mode-locking and this technique is used either to shorten the mode-locked pulses or to raise the pulse repetition frequency [16].

The active mode-locked fiber laser was built by using 3 m of Erbium doped fiber (EDF) which was pumped by a laser diode operating at 980 nm via a 980/1550 WDM fiber coupler, see Fig. 3(a). The peak absorption of the EDF (L-band) was 94.59 dB at 1530 nm. This WDM also has an integrated isolator for unidirectional operation. An EOM was placed in the cavity which can be operated at a maximum modulating frequency of 10 GHz. Since the EOM is polarization dependent, a polarization controller (PC1) is placed in the cavity before the EOM. This helps to achieve higher modulation and shorter pulses with wider spectra. The second polarizer (PC2) does not play a role in this active configuration but it will when PDMS/SWCNT SA is incorporated in the cavity. Therefore, we incorporate it in the active configuration such that the only difference between both configurations will be the PDMS/SWCNT film. The laser output is obtained from one port of a 3-dB fiber coupler. The cavity fundamental frequency is 19.23 MHz which corresponds to a laser cavity length of about 10.4 m. Using directional couplers at the laser output simultaneous measurements of the optical spectrum and second harmonic generation (SHG) autocorrelation are performed.

During active mode-locked laser operation, the RF frequency driving the EOM is chosen to match the 209th harmonic of the fundamental frequency, i.e., 4.0205 GHz. A stable pulse train is achieved with a pump power of 100 mW. At this pump power, optical spectrum and SHG autocorrelation trace of the laser

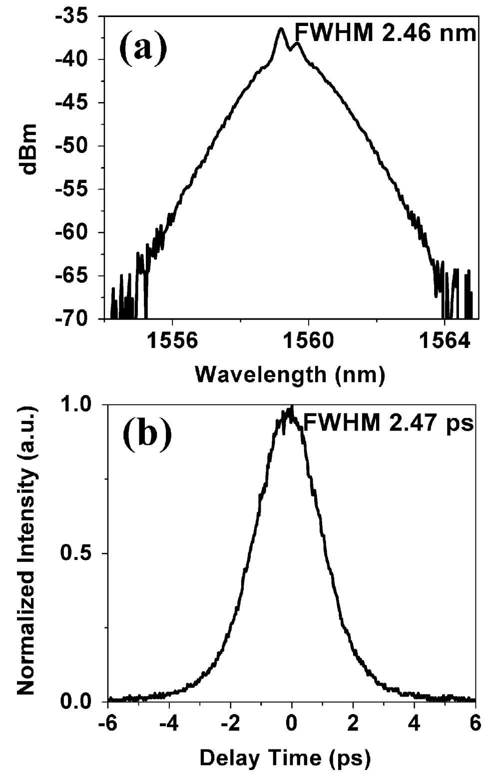

Fig. 4. (a) Optical spectrum. (b) Autocorrelation trace from the active mode-locked fiber laser.

output were measured, as shown in Fig. 4(a) and (b). The active mode-locked laser's central wavelength was 1559.45 nm with a FWHM of 2.46 nm, see Fig. 4(a). The FWHM of the autocorrelation trace was 2.47 ps, as shown in Fig. 4(b), corresponding to a deconvolved pulsewidth of 1.39 ps, assuming sech^2 time intensity profile. The time-bandwidth product was 0.42 (compared to a transform limited of 0.315). A maximum average output power of 8 mW was also measured.

The hybrid mode-locked laser was built by combining the active mode-locked system with the PDMS/SWCNT SA which was incorporated in the cavity, as shown in Fig. 3(b). In principle, the active modulation should give rise to pulse formation, and the addition of the SA should narrow the temporal width of the pulses [17]. The PDMS/SWCNT film was placed after the second polarization controller in the experimental setup of the active configuration, as shown in Fig. 3(b). Taking into account that the only difference between the active mode-locking and the hybrid setup is the insertion of the SA, i.e., all the experimental condition were the same as in the active mode-locked laser, thus any reduction of the temporal pulse-width should be fully attributed to the SA.

The length of the cavity was not significantly altered due to the PDMS/SWCNT thin film, and therefore the cavity fundamental frequency is the same. In order to achieve mode-locking the modulator was driven using the same modulation parameters as with active configuration, i.e., the amplitude modulation was operated to match the 209th harmonic of the fundamental frequency with the same modulation depth. A stable pulse train is achieved by applying a pump power of 231 mW, and also

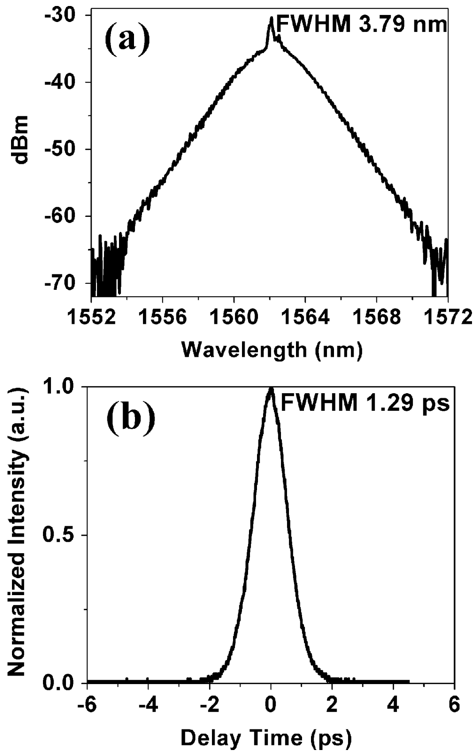

Fig. 5. (a) Optical spectrum. (b) Autocorrelation trace from the hybrid mode-locked fiber laser.

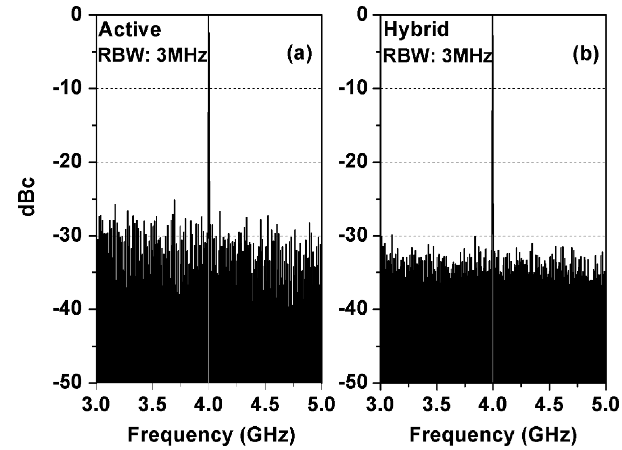

Fig. 6. Photodetected RF spectrum of (a) active and (b) hybrid mode-locked laser configurations.

adjusting the PC2 (due to the small film polarization dependence of the PDMS/SWCNT film. At this pump power, optical spectrum and autocorrelation trace of the laser output were measured, as shown Fig. 5(a) and (b). The hybrid mode-locked laser's central wavelength was 1562.18 nm with a FWHM of 3.79 nm, see Fig. 5(a). The FWHM of the autocorrelation trace was 1.29 ps, as shown in Fig. 5(b), corresponding to a deconvolved pulsewidth of 730 fs, assuming sech^2 time intensity profile. The time-bandwidth product was also 0.344, which is close enough to transform-limited sech^2 pulses [15]. A maximum average output power of 4 mW was also measured.

When comparing the active and hybrid mode-locked results, we can easily notice that the pulsewidth duration is 48% narrower when going from the hybrid configuration. Additionally, the optical spectrum generated by the hybrid configuration is 54% wider than the spectrum generated by the active one.

The temporal narrowing of the pulses when going from active to hybrid configuration is related to the SA properties of the PDMS/SWCNT composite. It is well known that a SA will introduce low loss to light with high intensity and high loss to light with low intensity. Therefore, when the pulses circulating through the cavity reach the PDMS/SWCNT, the central part of the pulse with high intensity is transmitted with low loss, whereas the weaker leading and trailing edges of the pulse suffer higher losses [16]. This pulse-width reduction is of course correlated with an increment in the band-width of the optical spectrum. The amount of narrowing is then dependent on the non-saturable losses of the PDMS/SWCNT SA, with higher non-saturable losses providing narrower pulses and viceversa. In our experiments we used the highest SWCNT concentration for the maximum film thickness that can be used between the FC-APC connectors, which correspond to the maximum pulse-width reduction achievable with the current configuration.

We then measured the RF spectrum of both configurations around 4 GHz, as shown in Fig. 6, we can notice a remarkable difference. It is well known that harmonic operation of mode-locked lasers gives rise to noisy laser performance due to the limited correlation between the intra-cavity pulses, which is demonstrated as supermode noise spurs (SNS) in the RF spectra of the photodetected pulse train [18]. As shown in Fig. 6(a), for the active configuration we have an SNR of less than 30 dB, and the SNS exhibits considerable fluctuation. However, in the case of the hybrid configuration the SNR was improved by approximately 5 dB ($\sim$35 dB), but more importantly is the fact that the SNS fluctuations were considerable reduced, see Fig. 6(b). This result is very important because such effects occur when some kind of frequency stabilization is implemented in the cavity, for example by adding a Fabry-Pérot etalon in the cavity [12]. In fact, there are a couple of references that mention such phase stabilization for passive mode-locked lasers using SWCNTs [19], [20]. In our case, the PDMS/SWCNT SA acts as an amplified spontaneous emission (ASE) suppressor outside the pulse window because the intensity outside the window is weaker. Since the SNS noise is related to the ASE, reducing the ASE effectively reduces the SNS noise. The key factor here is that the noise is reduced when working with the hybrid mode-locked system.

Based on our experiments, the SNS could be further improved by increasing the absorption of the film (currently 32%) and also the modulation depth. In order to fulfill both requirements, we have to completely isolate the SWCNTs in the polymer matrix, and this is a limitation for thin films within an all-fiber system. If we make the SWCNTs concentration lower to isolate the nanotubes, thus the film thickness has to increase to obtain the desired absorption. This will make the connector losses too high. Increasing the concentration is not an option because the formation of bundles is increased which have detrimental effects for the film as the intracavity power is increased. Therefore, this should be done using a specialty fiber that could allow

low concentrations of SWCNTs, while attaining high absorption values by increasing the length of the fiber. These all-fiber SWCNT SA are currently under development. Nevertheless, such effect is a plus when adopting a hybrid mode-locking. We should also mention that in our experiments the maximum modulation frequency was close to 4 GHz, but this frequency value was limited by the available equipment. In principle, higher modulation frequencies should be feasible. The key advantage of using this hybrid configuration is that we can obtain pulse trains with higher repetition rates while maintaining the narrow pulses achieved by passive SA. In fact, the pulses get narrower with the square root of the period of the laser [13], which will be also beneficial for our hybrid system in order to obtain even narrower pulses.

V. Conclusion

In summary a hybrid mode-locked Erbium fiber laser was proposed and implemented. This configuration has the advantage over current mode-locked systems that can provide a high repetition rate while attaining ultrashort pulses (with fs temporal duration). The SA was developed using a PDMS/SWCNTs thin film composite, which is inexpensive and simple to fabricate. The insertion of the SA in a hybrid mode-locked laser narrows the pulse-width as compared to the active mode-locked laser by a factor of two, while also reducing the SNS fluctuations on the RF noise. A pulsewidth of 730 fs was generated at a repetition rate of 4 GHz, and a maximum output power was 4 mW. A reduction in the noise of the photodetected RF spectrum was also observed in the hybrid system.

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I. Hernandez-Romano received the B.S. degree in physics from the Facultad de Ciencias Fisico Matematicas, BUAP, and the M.S. degree in optics from National Institute of Astrophysics, Optics and Electronics, where he is currently working toward the Ph.D. degree in optics.

His current research interests include ultrafast optics and fiber sensor.

Mr. Hernandez-Roman is a member of the Optical Society of America.

Josue Davila-Rodriguez received the B.S. degree in engineering physics from Tecnologico de Monterrey, in 2006. He is currently working toward the Ph.D. degree at the Center for Research and Education in Optics and Lasers (CREOL), University of Central Florida, Orlando.

He joined CREOL as a Researcher, in 2007. His research focuses on novel mode-locked laser sources and applications.

Dimitrios Mandridis received the B.S. degree in applied physics from the National Technical University of Athens, Athens, Greece, in 2004, and the M.S. and Ph.D. degrees in optics from the University of Central Florida, Orlando, in 2007 and 2011, respectively.

His research focuses on laser sources for photonic analog-to-digital conversion, laser radars and laser ranging, low-noise lasers.

J. J. Sánchez-Mondragón received the B.Sc. degree in physics from the National Autonomous University of México, D.F., México, in 1974, and the M.Sc. and Ph.D. degrees in optics from Rochester University, Rochester, NY, in 1980.

He is currently a Researcher with the Optics Department, National Institute for Astrophysics, Optics, and Electronics (INAOE), Puebla, México. His current research interests include the study of quantum optics, and the development of nanostructured photonic devices.

Dr. Sánchez-Mondragón is a Fellow of the Optical Society of America. He received the AMO Prize.

Daniel A. May-Arrioja received the B.Sc. degree in electrical engineering from the Instituto Tecnológico de Tuxtla Gutierrez, Mexico, in 1996, the M.Sc. degree in optics from INAOE, Mexico, in 1998, and the Ph.D. degree in optics from CREOL, The College of Optics and Photonics, at the University of Central Florida, Orlando, in 2006.

His current research interests include integrated photonics and fiber optics devices with applications to lasers, sensors and biosensors, and MEMS.

Peter J. Delfyett (M'94–SM'96–F'02) is the University of Central Florida Trustee Chair Professor of Optics, ECE and Physics at The College of Optics & Photonics, and the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida.

Prior to this, he was a Member of the Technical Staff at Bell Communications Research from 1988–1993, where he concentrated his efforts towards generating ultrafast high power optical pulses from semiconductor diode lasers, for applications in applied photonic networks. Some of his technical accomplishments were the development of the world's fastest, most powerful mode-locked semiconductor laser diode, the demonstration of an optically distributed clocking network for high speed digital switches and supercomputer applications, the development of the lowest ever timing jitter from a mode-locked diode laser, and breaking the terabit per second data rate barrier from a single semiconductor laser. He has published over 500 articles in refereed journals and conference proceedings, has been awarded 25 U.S. patents.

Dr. Delfyett is a Fellow of the Optical Society of America, Fellow of IEEE/LEOS, and served as member of the Board of Governors of IEEE-LEOS and the Board of Directors of OSA. He has served as Editor-in-Chief of the IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, associate editor of the IEEE PHOTONICS TECHNOLOGY LETTERS, and Executive Editor of IEEE LEOS Newsletter. He has been awarded the National Science Foundation's Presidential Faculty Fellow Early Career Award for Scientists and Engineers, which is awarded to the Nation's top 20 young scientists. He has also received the University of Central Florida's 2001 Pegasus Professor Award, which is the highest honor awarded by the University.