Coherent supercontinuum generation using Er-doped fiber laser of hybrid mode-locking

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Supercontinuum generation is performed using femtosecond laser pulses produced by combining two distinct mode-locking mechanisms of nonlinear polarization evolution with saturable absorption on an Er-doped fiber oscillator. The generated supercontinuum yields a high level of spectral visibility of 93%, without the presence of spontaneous emission of post-amplification, being well suited for precision spectroscopy, broadband interferometry, and coherent telecommunications. © 2014 Optical Society of America

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The frequency comb of mode-locked femtosecond lasers needs to be spectrally broadened to a supercontinuum for its various applications such as spectroscopy, frequency metrology, communications, and tomographic imaging [1–4]. In the last decade, the nonlinear spectral broadening of fiber-based lasers was extensively investigated to improve the capability of supercontinuum generation in terms of the spectral bandwidth and also phase coherence by diversifying nonlinear fiber microstructures, mode-locking mechanisms, and dispersion control schemes [5–9]. As a result, the Er-doped fiber laser combined with a highly nonlinear fiber (HNLF) is now widely used as a convenient means of generating an octave-spanning supercontinuum around a ~1.5 μm center wavelength [8–12]. Coupling the Er-doped fiber laser to the HNLF for supercontinuum generation requires an intermediate power amplifier made of the same fiber (Er-doped fiber amplifier, EDFA) to boost up its oscillator output power so as to induce strong spectral broadening within the HNLF. However, the EDFA-based power amplification creates the problem of deteriorating the phase coherence of the generated supercontinuum, which is attributable mainly to the white phase noise made by the amplified spontaneous emission (ASE) within the EDFA [13,14]. In this Letter, in order to suppress the ASE-induced coherence problem, we present an Er-doped fiber laser oscillator designed to operate by combining two distinct mode-locking schemes of nonlinear polarization evolution (NPE) and saturable absorption (SA). The hybridized mode-locking produces strong output pulses to enable supercontinuum generation directly through the HNLF without external power amplification. In consequence, the resulting supercontinuum sustains high coherence free from the EDFA-induced ASE or parasite nonlinear noise.

Figure 1(a) elucidates the hybrid mode-locked femtosecond laser oscillator configured in our study—which is referred to as the hybrid oscillator hereafter. For comparison, an Er-doped fiber oscillator based on NPE mode locking shown in Fig. 1(b) is also used in our experiments—called the NPE oscillator. The hybrid oscillator operates on two distinct mode-locking mechanisms, NPE and SA, of which design details were explained in our previous publication [15]. The hybrid mode-locking is intended to reduce nonlinear phase

![Fig. 1. Comparison of supercontinuum generation with a 130 mW power. (a) The hybrid oscillator and (b) the NPE oscillator coupled to an EDFA. The autocorrelation along with corresponding optical spectrum (inset) for each oscillator is given in (c) and (d), respectively. Abbreviations are LD, laser diode; WDM, wavelength division multiplexer; EDF, Er-doped fiber; QWP, quarter-wave plate; HWP, half-wave plate; PBS, polarization beam splitter; OC, output coupler; SA, saturable absorber; ISO, isolator; HNLF, highly nonlinear fiber; NPE, nonlinear polarization evolution; EDFA, Er-doped fiber amplifier.](http://dx.doi.org/10.1364/OL.39.002986)
noise by removing parasitic dispersive waves creating satellite pulses. Consequently, with an enhanced modelocking efficiency, the hybrid oscillator is capable of providing high output power in a clean pulse shape, with 98.5% of the pulse energy being concentrated on the main lobe as illustrated in Fig. 1(c). The hybrid oscillator produces 146 fs duration pulses at a 50 MHz repetition rate with a 130 mW average power. A 600 nm long HNLF with a 1550 nm zero-dispersion wavelength is spliced directly to the hybrid oscillator for supercontinuum generation. On the other hand, the NPE oscillator of 10 mW output power is connected to an EDFA pumped by two pump laser diodes. The average output power, pulse duration, and pulse repetition rate of the NPE oscillator are carefully adjusted to be comparable to those of the hybrid oscillator after post-amplification. The final temporal pulse shape of the NPE oscillator injected to the same HNLF used for supercontinuum generation is shown in Fig. 1(d).

The supercontinuum generated by the hybrid oscillator is presented in Fig. 2(a), of which the spectral range is found to span more than an octave, as measured using two optical spectrum analyzers (OSAs)—the short wavelength section by MS9710C from Anritsu and the long wavelength section by AQ6375 from Yokogawa. When compared to the counterpart produced by the EDFA-amplified NPE oscillator shown in Figs. 2(b) and 2(c), the supercontinuum of the hybrid oscillator is ∼30 nm broader at the short wavelength end with higher spectral power by a factor of 1.7. The spectral power and width enhancement is interpreted due to lowered ASE and also higher energy concentration in the pulses generated directly from the hybrid oscillator. To our knowledge, no attempt has previously been reported on an amplifier-free octave-spanning supercontinuum using an Er-doped fiber laser, even though several cases are available for Yb-doped fiber lasers [16,17].

The phase coherence of the frequency comb or supercontinuum of the hybrid oscillator (and the NPE oscillator) can be quantified by measuring the interference visibility between two distinct pulses emitted at different times [18–20]. For the purpose, an unequal-path Michelson-type interferometer illustrated in Fig. 3(a) is used here, which is fundamentally immune to broadband amplitude noise. The two-arm interferometer is composed of single-mode fibers with the optical path difference (OPD) being equal to the spatial interval between the two consecutive pulses ∼6.0 m for a 50 MHz pulse repetition rate. The interference of the two pulses is precisely adjusted by translating the mirror sitting on a microstage activated by a piezoelectric actuator at the measurement arm of the interferometer. In addition, the polarization overlap and spatial mode matching between the two pulses in interference are assured by employing an in-line fiber polarizer, a polarization controller, and an optical attenuator. The resulting wavelength-resolving interferogram is monitored using an OSA (MS9710C, Anritsu) with

Fig. 2. Comparison of generated supercontinua. (a) An octave-spanning supercontinuum generated by the hybrid oscillator. (b) Spectral comparison with another supercontinuum generated by the EDFA-amplified NPE oscillator. (c) Magnified spectra at the shorter wavelength end.

Fig. 3. Frequency comb phase coherence test. (a) Unequal-path interferometer used to monitor the spectral interference visibility. (b) Spectral interferogram of the hybrid oscillator. (c) Spectral interferogram of the EDFA-amplified NPE oscillator. (d) Comparison of spectral visibility. FC, fiber coupler; FM, fiber mirror; A, attenuator; PC, polarization controller; L, lens; M, mirror; S, stage; P, polarizer; OSA, optical spectrum analyzer.
a 0.05 nm resolution. Finally, for each wavelength, the interference visibility $V$ is calculated as $V = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}})$, where $I_{\text{max}}(I_{\text{min}})$ denotes the maximum (minimum) interference intensity.

The measured spectral visibility of the frequency comb of the hybrid oscillator before supercontinuum generation is shown in Fig. 3(b), while that of the EDFA-amplified NPE oscillator in Fig. 3(c). The hybrid oscillator offers a higher level of phase coherence with an averaged spectral visibility $\sim 96\%$. In comparison, the visibility of the EDFA-amplified NPE oscillator remains at an average of $\sim 83\%$ and even reduces to $69\%$ in the wavelength region, where the ASE of the EDFA becomes dominant. The ASE-induced degradation would become more severe when the amplification gain of the EDFA has to be increased for seed pulses having lower power or longer duration, which is not desirable at all for most of applications such as spectroscopy, interferometry, and telecommunication. In contrast, by combining the two distinct mode-locking mechanisms of NPE and SA, the hybrid oscillator effectively suppresses the intra-cavity ASE, which otherwise would severely degrade the phase coherence.

The spectral visibility of the supercontinuum generated by the hybrid oscillator is finally compared with that of the EDFA-amplified NPE pulses, as shown in Fig. 4. All the optical parameters of the interferometer of Fig. 4(a) are carefully adjusted to yield a wide spectral coverage from 1100 to 1750 nm. The spectral interferogram shown in Fig. 4(b) is a result of stitching 10 individual interferograms, each covering a different 65 nm wavelength range with a 0.05 nm resolution limited by the used OSA. The supercontinuum of the hybrid oscillator provides a higher level of phase coherence over the whole wavelength range with an averaged visibility of $93\%$. In the meanwhile, the NPE oscillator offers an average visibility of $87\%$ with a minimum of $40\%$ at wavelengths around 1560 nm, where the ASE spectrum of the EDFA becomes strong, as shown in Fig. 4(c). This visibility decrease is basically similar to the decrease seen in Fig. 3(d) before the spectral broadening, but the extent of decrease is found to be more severe, 13%, indicating that the coherence degradation due to ASE is augmented further in the spectral broadening process. Two more dips are found in the spectral visibility around 1270 and 1670 nm wavelengths, which are likely to be attributed to the uneven spectral power density distribution within the supercontinuum of the NPE oscillator.

In conclusion, the hybrid oscillator proposed in our work is capable of generating a highly coherent supercontinuum by seeding strong pulses of 130 mW average power directly into a HNLF without any post-amplification. The phase coherence reaches a level of $99\%$ averaged over an extensive wavelength range, proving to be an attractive workhorse for diverse applications where the phase coherence is essential. Further work is planned to demonstrate the capabilities of the hybrid oscillator through f–2f stabilization without EDFA amplification.

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References


