Wavelength and repetition rate tunable mode-locked laser at up to 640 GHz using reconfigurable wavelength selective switch

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Abstract—**We demonstrate the first wavelength and repetition rate tunable mode-locked fiber laser at ultra-high repetition rates of up to 640 GHz. The mode-locking is based on dissipative four-wave mixing with a reconfigurable wavelength selective optical switch as the spectral filter.**

Introduction

The generation of ultra-high repetition rate pulse sources has been a very active research area in recent years [1], [2]. The most common technique for generating high repetition rate pulses is based on electrically modifying a cavity parameter by e.g. driving an amplitude modulator. This method has been widely adopted in e.g. telecommunication systems and wavelength tunable lasers at 40 GHz repetition rate have been demonstrated [3]. However these lasers are generally limited by the bandwidth of the underlying electronic system and in order to to increase the repetition rate beyond 100 GHz new all optical techniques have to be adopted. Passive mode-locking techniques offer the potential to overcome the limitations posed by electronic bandwidths and repetition rates well beyond 100 GHz have been achieved [1]. Although some passive mode-locked lasers with selectable repetition rates have been demonstrated [4], their wavelength was fixed. Other techniques, although exhibiting wavelength and repetition rate tunability, require a significant change to the setup in order to operate at different repetition rates [5].

We demonstrate here the first wavelength and repetition rate tunable fiber laser at ultra-high repetition rates. The repetition rate and wavelength of the laser can be easily varied without changes to the experimental setup by simply reconfiguring the Fourier-domain programmable optical processor (FD-POP) acting as a spectral filter.

Principle

In this experiment we use so-called dissipative four-wave mixing [6], which has previously been shown to yield ultra-high repetition rates at very high average output powers [7]. The central element of this technique is a combination of a Fabry-Perot filter with a bandpass filter, based on a commercially available FD-POP, the WaveShaper 4000E from Finisar. We are thus able to alter the repetition rate and wavelength of the pulse train by simply reconfiguring the FD-POP. The mode-locking is achieved by the two Fabry-Perot modes at the center of the bandpass filter experiencing gain and distributing their energy to modes detuned from the center of the bandpass filter via four wave mixing (FWM). Due to the bandpass filter these higher-order modes experience a net loss and the dissipation guarantees a unidirectional energy transfer from the central modes to the higher-order modes. Therefore a constant phase relationship between modes is ensured and the laser exhibits a train of pulses with a repetition rate given by the free spectral range (FSR) of the Fabry-Perot filter.

Experimental setup

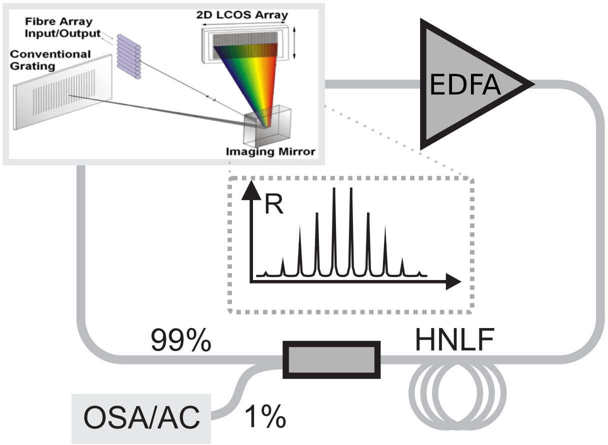

Fig. 1. Experimental Setup. The WaveShaper is depicted in the right hand corner. EDFA: Erbium-doped fiber amplifier, HNLF: highly nonlinear fiber, OSA: optical spectrum analyzer, AC: autocorrelator. The inset shows a typical filter spectrum of the WaveShaper.

The experimental setup is depicted in figure 1. The laser is realised in a simple ring cavity configuration using an Erbium-doped fiber amplifier as the gain element and the nonlinearity is provided by 33 m of highly nonlinear fiber (HNLF). The spectral filtering, which is essential for the mode-locked operation of the laser is performed by the WaveShaper FD-POP, which allows for easy reconfiguration of the spectral filter enabling the wavelength and repetition rate tuning of the laser. A typical filter spectrum is shown in the inset of figure 1. The output spectrum or autocorrelation of the laser is monitored behind a broadband coupler situated in between the HNLF and the FD-POP with 99% of the power reinjected into the cavity. Additionally the laser can contain an inline polarizer and a polarization controller to adjust the polarization state of the laser and optimize the FWM. A detailed description of the FD-POP is given in Ref [8] suffice to say here that the FD-POP works by diffracting the input light onto a two-dimensional liquid crystal on silicon (LCoS) array. Applying phase variations across either the horizontal or vertical dimension of the array controls the spectral phase and intensity respectively. The bandwidth of the device ranges from 1524 nm to 1570 nm with a spectral resolution of approximately 10 GHz. In this experiment we only use the attenuation capabilities of the device. By setting the device to full attenuation and only selectively unblocking certain pixel columns we can create a Fabry-Perot type filter with the FSR being a multiple of 10 GHz. Applying different attenuations to the unblocked pixels creates a bandpass envelope over the Fabry-Perot filter resulting in the spectral filter necessary for the mode-locking process.

Results

The experimental result are presented in figure 2. The left hand column displays the optical spectra of the laser at various wavelengths and repetition rates, while on the right hand side we can see the corresponding autocorrelation traces. Figure 2(a) and (b) demonstrate the spectrum and the autocorrelation of the laser when the WaveShaper is set to a filter with a FSR of 160 GHz centered at about 1561.5 nm. As expected the FSR of the Fabry-Perot filter is reflected in the optical spectrum which is made up of a collection of discrete modes separated by 160 GHz. The autocorrelation demonstrates the mode-locked operation of the laser showing a train of pulses with a period of about 6.25 ps in agreement with the 160 GHz repetition rate. The width of the autocorrelation pulses is approximately 2.3 ps. The wavelength tunability of the laser can be observed by comparing figure 2(a) and figure 2(c). In figure 2(c) the center-wavelength of the filter was adjusted to about 1542 nm demonstrating that is possible to vary the wavelength of the laser by almost 20 nm. This large tuning range of exemplifies the advantages of the FD-POP over other tuning methods such as stretching a fiber Bragg grating. Note that the different shape and number of modes of the spectrum compared to figure 2(a) can be attributed to the different gain profile of the EDFA at the different wavelengths. This could however be easily overcome by e.g. using a gain flattened amplifier. It also does not have a detrimental effect on the resulting pulse train.

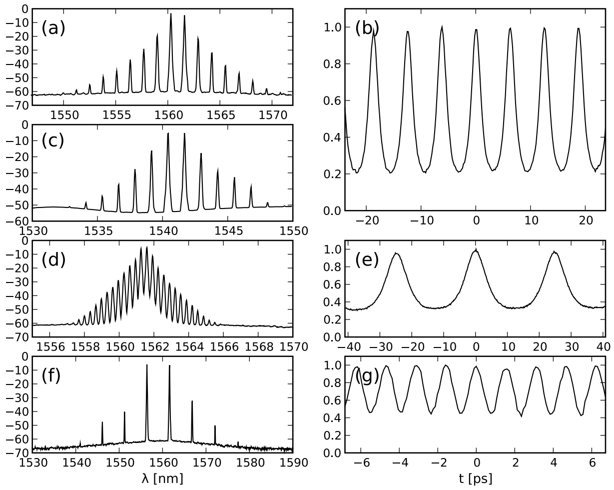

Fig. 2. Left hand column: Output spectra of the laser operating at (a) 160 GHz repetition rate and 1561.5 nm wavelength, (c) 160 GHz and 1542 nm wavelength (d) 40 GHz and (f) 640 GHz. Right hand column: Corresponding autocorrelation traces of the laser at (b) 160 GHz (e) 40 GHz and (g) 640 GHz repetition rate.

Apart from being able to tune the center wavelength of the laser it is furthermore possible to select the repetition rate of the laser by changing the frequency spacing of the reflecting spectral lines of the FD-POP, demonstrated in figure 2(d) through (g). We should note that the number of modes created in the case of the 40 GHz laser is limited by the shape of the bandpass envelope of the spectral filter and could easily be increased by choosing a lower attenuation for the higher order modes. The laser operating at 640 GHz on the other hand is currently limited by the bandwidth and maximum gain of the EDFA inside the setup. The power in the fundamental modes required to create higher-order modes is dependent on the mode separation between the modes. Therefore, to create a mode number similar to the 160 GHz laser in the case of 640 GHz laser requires a significantly larger gain, which the current EDFA could not provide. The duty cycle of the 640 GHz pulse train is thus relatively close to unity. We would like to stress however that we are not merely observing a beating between the two fundamental modes which is evident by the number of modes in the spectrum. We are currently working on improving the duty cycle of the high-repetition rate pulse trains by using a stronger EDFA.

Conclusion

In conclusion we have demonstrated the first wavelength and repetition rate tunable passively mode-locked laser reaching repetition of up to 640 GHz. The repetition rate and wavelength of the laser can be easily and possibly remotely selected by reconfiguring the Fourier-domain programmable optical processor acting as the filtering element. A tuning range of 20 nm in the C-band was shown, demonstrating the advantage of the optical processor over other filtering elements.

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