Injection locking for stable all-optical pulse generation via gain-induced FWM

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We propose and demonstrate a technique to stabilize pulse generation based on gain-induced four wave mixing (FWM) via injection locking with no feedback. Robust and low-phase noise pulse generation was achieved. Pulse-train generation from 230 MHz to ~76 GHz with a linewidth of ~1 Hz is experimentally demonstrated. The injection locking effectively narrows the linewidth of the generated pulse by four orders of magnitude. The fiber ring cavity reduces the sideband phase noise by 100 times and suppresses the residual injection signal by three orders of magnitude.

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Stabilized, tunable, photonic-based microwave and pulse generation techniques have been extensively investigated as they are desirable in many fields of applications such as telecommunication systems, radar systems, and modern metrology [1,2]. Stable pulse or microwave source generation techniques that were demonstrated previously often require a stable RF signal source, which increases the systems cost and complexity. For example, an optical pulse source can be generated using active mode-locking techniques that employ an electronically driven active medium in the ring cavity [3,4]. However, the pulse repetition rate, or microwave frequency, is usually limited by the characteristics and in particular, the bandwidth of the RF source. Another approach to achieving a high-quality optical or microwave signal utilizes an optical phase-locked-loop (OPLL). This technique also requires a stable RF signal as a reference. In addition, for this technique to achieve effective phase locking with relative ease, stringent constraints for a very short feedback loop are often required and the optical pulse or microwave signal should have relatively low phase fluctuation before directing it into the OPLL [5].

Injection locking techniques have offered a very promising solution for photonic-based microwave and pulse generation [6,7]. They allow not only the widely tunable optically controlled generation of pulses and microwave signals, but also offer a performance that is characterized by high frequency stability. However, the intrinsic laser noise resulting from the drift of bias conditions such as the drive current and the temperature controller degrades this stability. As such it is often the case that another stabilization scheme is required. It is customary in these systems to combine the injection locking with an OPLL [6] for improved signal quality. To eliminate the requirement for expensive electronic components, a stabilization technique that combines the injection locking and an optical feedback loop has been proposed [8]. In that work, a narrow linewidth with 50 kHz has been achieved. The stabilized microwave signal is then used for pulse generation through a highly nonlinear fiber [7]. Thus, the operating wavelength is limited to the tunability of the injection locking source laser.

Recently, optical pulse-trains that are generated in an all-optical setting based on gain-induced FWM in an SOA have been demonstrated [9]. A unique advantage of this versatile approach is that it allows optical control of the repetition rate, which could be tuned by controlling the frequency difference between the two laser sources. However, in this first demonstration, the uncorrelated phase of these two light sources directly results in an unstable performance of the generated pulses. Moreover, the uncorrelated phase will also cause intensity fluctuations in the generated pulses since the FWM process is highly dependent on the phase profile of the two laser sources. In this work, we drastically improve upon this recent work [9] by using injection locking. Robust and low-phase noise pulse generation ranging from 230 MHz to ~76 GHz with a linewidth of ~1 Hz is experimentally demonstrated. The injection locking effectively narrows the linewidth of the generated pulse by four orders of magnitude. The fiber ring cavity reduces the sideband phase noise by 100 times and suppresses the residual mode of injection by three orders of magnitude.

The technique of generation can be explained using Fig. 1, which outlines the principle of the proposed technique for stable all-optical pulse generation. In the demonstration, the injection locking part contains a femtosecond-fiber laser (FFL) with two distributed feedback (DFB) semiconductor lasers. The FFL is a passive mode-locked laser with a 10 MHz repetition rate at a central wavelength of 1550 nm. It is first filtered using a 0.5 nm narrow band pass filter and amplified before being injected into two DFB lasers. The two slave

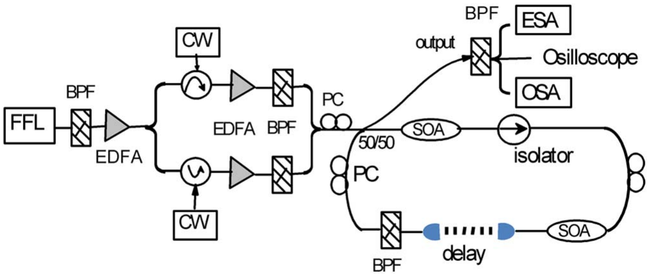

Fig. 1. Experimental setup for all optical microwave generation based gain-induce FWM. PC, polarization controller; BPF, band pass filter; FFL, femto-fiber laser; ESA, electrical spectrum analyzer; and OSA, optical spectrum analyzer.

DFB lasers were linearly polarized, providing a single-mode emission with an output power of up to 10 dBm. The module did not contain any isolators, which allowed optical injection via the front facet. Injection locking was observed by splitting off a portion of the passive mode-locked laser prior to injection and recombining it with the slave laser output. An amplifier is used to enhance the power of the slave laser output followed by a band pass filter, which eliminates the ASE noise. The combined signal from the two locked DFB lasers is then injected into the main ring laser to modulate the gain of an SOA as can be seen in Fig. 1. The main fiber ring cavity is comprised of two SOAs (Kamelian nonlinear SOAs & Thorlab BOA); the first SOA functions as the gain and modulation medium while the second controls the net gain of the cavity. The Kamelian SOA is specially designed for high-nonlinearity with a typical small signal gain of 15 dB at 300 mA bias and a saturation output power of 10 dBm. The Thorlab SOA has a typical small signal gain of 27 dB at 600 mA bias and a saturation output power of 17 dBm. The polarization extinction ratio is 18 dB. Typical drive currents for the SOAs are 250 and 500 mA. The tunable flat-top OBPF has a 3 dB bandwidth of ∼6.8 nm that is centered at ∼1561 nm. It is employed to perform wavelength selection of the output and filter the injected beating signal. The central wavelengths of the DFBs are ∼1552 nm. They can be tuned within a range of ∼4 nm using a temperature controller. By fixing the central wavelength of one DFB while tuning the other central wavelength, beating signals between 230 MHz and 76 GHz are generated and examined. The tunability is achieved by the temperature tuning and the drive-current tuning. The external beating signal is coupled into the main fiber ring laser cavity at a power level of 7 dBm. Optical pulses are then generated at output of the laser.

Injection locking is monitored and optimized using a 35 GHz photo-detector and an RF spectrum analyzer. We first injection-lock one DFB laser and recombine the output of the DFB laser with the output of the FFL. The beating of the recombined signal can be observed using the RF spectrum analyzer. By fine tuning the central wavelength of the DFB toward one of the comb mode of the FFL, a narrow linewidth beating signal can be observed at the multiples of the FFL repetition rate. This corresponds to the injection-locked state. Another DFB laser is then injection-locked to the FFL using the same technique. Figure 2(a) also shows the optical spectrum of the two CW lasers along with the spectrum of the FFL laser. The central wavelength of the two DFB lasers are ∼1552.442 nm and ∼15552.628 nm, corresponding to a ∼23 GHz beating frequency. The RF spectrum of the slave laser in the free running and locked states are shown in Fig. 2(b). As can be seen, in the unlocked state, the beating signal exhibits a much wider linewidth of ∼8 MHz. When the two slave lasers locked to the FFL, the beating signal has a very narrow linewidth in the range of a few Hz. However, while the DFB laser can be locked to only a single comb mode of the FFL, the nearby unlocked comb modes also experience some amplification by passing through the gain medium of the DFB laser. Consequently, we observe the magnitude of the residual comb mode in the RF spectrum of the injection-locked beating signal.

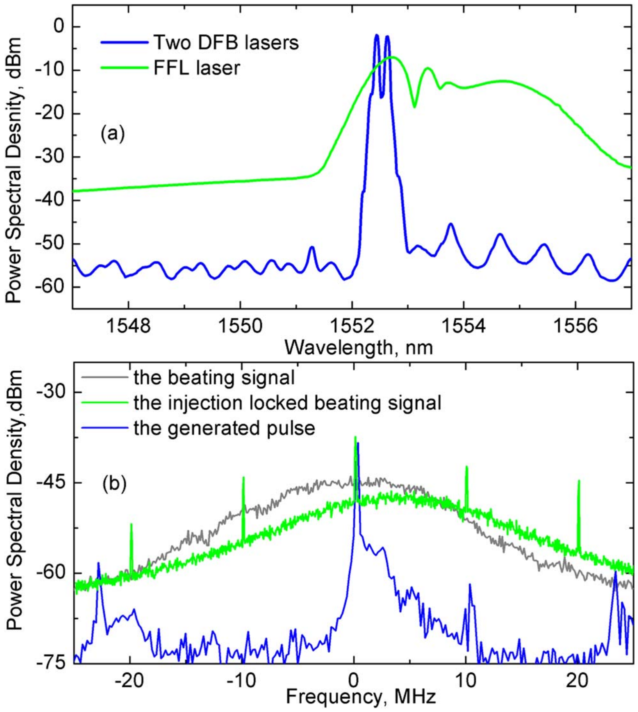

Fig. 2. Measured (a) spectra of the FFL laser and two DFB laser outputs. (b) Linewidth of the unlock, locked beating signal, and the generated pulse.

Once locking is achieved, the injection-locked beating signal is then injected into the fiber ring laser to generate the pulse by gain-induced FWM [9]. The linewidth of the generated pulse is also characterized and shown in Fig. 2(b). The RF spectrum of the pulse preserves the narrow linewidth of the injection-locked beating signal, but with a suppressed sideband. The suppressed sideband noise is reduced by two orders of magnitude in comparison to the injected beating signal. This noise reduction results from the Q-factor of the main cavity of the SOA-based fiber ring laser. The fiber ring laser has a free spectral range of ∼23 MHz, which corresponds to a cavity length of ∼8.6 m. Thus, the observed residual comb mode from the FFL in the injection-locked beating signal will be highly suppressed in the external fiber ring cavity as can be seen from Fig. 2(b). This reduced noise is highly desirable for certain applications, which utilize injection-locking such as optical arbitrary waveform generation [10], and is a direct consequence of combing the injection-locking and gain-induced FWM pulse generation techniques [9].

To understand the extent by which the sideband noise is reduced, we measure the single side band (SSB) noise of the injection-locked beating signal and the generated pulses. Figure 3(a) shows the measured SSB noise. As can be clearly seen; after the fiber ring laser, the generated pulse preserve the linewidth of the injection-locked beating signal. After a frequency offset of 25 KHz, the SSB noise is suppressed by more than 100 times due to the cavity quality factor. The peak at 10 MHz from the original FFL comb is also suppressed by three orders of magnitude. The peak at 23 MHz corresponds to amplitude

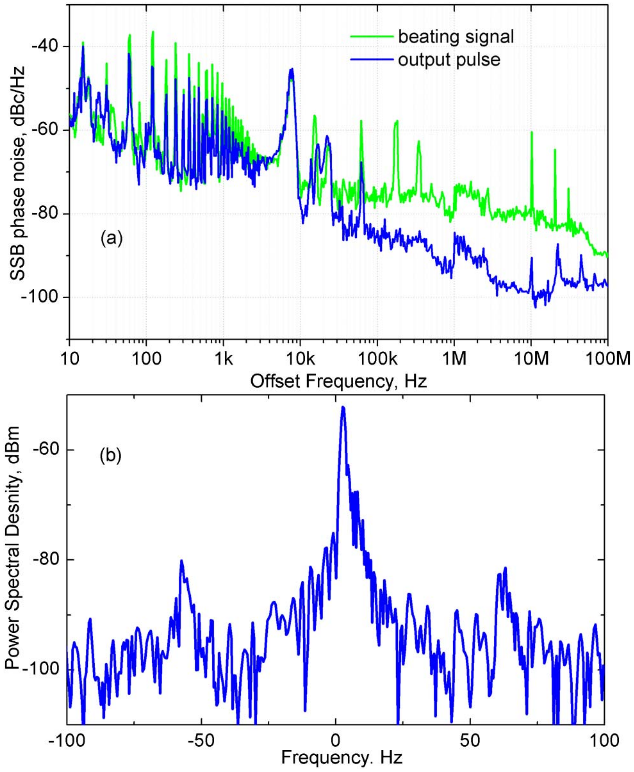

Fig. 3. (a) Measured single sideband noise characteristics of the output optical pulse and injection locked beating signal. (b) Zoomed linewidth measurement of the generated pulse.

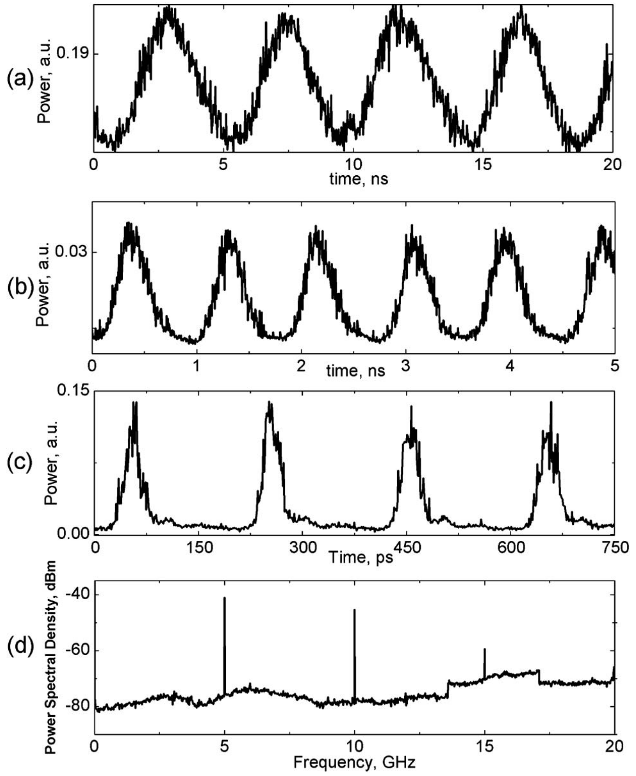

Fig. 4. Generated pulse trace at different repetition rates: (a) 230 MHz, (b) ~1.15 GHz, and (c) ~5 GHz. (d) The corresponding electrical spectrum of the pulse at 5 GHz.

noise peaks, which are introduced by the fiber ring cavity. We also examined the measured linewidth of the generated pulse closely. Fig. 3(b) is the RF spectrum over a 200 Hz range with a 1 Hz resolution, showing that the generated pulse has a linewidth of ~1 Hz, the same as that of the injection-locked beating signal. The measured linewidth of the pulse is ~22 KHz when the two DFB lasers are not injection locked [11]. Thus, the injection locking effectively narrows the linewidth of the generated pulse by more than four orders of magnitude. Using temperature tuning of the DFB lasers, we generate the injection-locked beating signal from 230 MHz to ~76 GHz. It is important to emphasize that the repetition rate tuning resolution also depends on the temperature tuning resolution. However, the drive current of the DFB laser can be also utilized to finely adjust the wavelength tuning of the emission wavelength.

The fiber ring laser initially operates in a CW mode (i.e., without external injection). The CW source is stable and is lasing at wavelength ~1563.8 nm with an average power of 5 dBm. By injecting the locked beating signal into the fiber ring laser, we generate the optical pulse with repetition rate ranging between 230 MHz and ~76 GHz. We first generate and fully characterize the optical pulse at a low repetition rate. The temporal waveform of the generated pulse is monitored using an ultrafast oscillocope with an 80 GHz photodetector. Figure 4 shows the trace of the generated pulses at different repetition rates. By increasing the power of the injection-locked beating signal, the generated pulse duration can be reduced, which corresponds to the generation of more harmonics in the frequency combs. With the injection power increasing from 3 to 10 mW, the full width half-maximum (FWHM) of the pulse duration of a 5 GHz pulse train is reduced from ~100 ps to ~32 ps. The pulse trace with a ~32 ps FWHM for 5 GHz is shown in Fig. 4(c). The corresponding electrical spectrum of the 32 ps pulse is also shown in Fig. 4(d). It clearly shows that higher order harmonics are generated with higher injection power. Even shorter pulses can be obtained by increasing the input power of the CW lasers. This is because the stronger external injection causes a deeper gain modulation, resulting in a narrow-pulsewidth. This has been observed in previous demonstrations with no injection-locking [9].

We then generate the pulse train with a 76 GHz repetition rate. Figure 5(a) shows the measured optical spectrum of the generated pulses. The asymmetric spectrum is because the CW source is lasing (without injection) at the right side of the band pass filter so some of the generated frequency comb components are eliminated by the band pass filter. As is evident from the figure, there exists an intensity unbalance between the frequency combs of the generated optical pulse. This is because of the finite and in this case insufficient nonlinearity of the SOA that is used in the cavity. SOAs with higher nonlinearity can remedy this; to measure the temporal profile of the generated pulses, we place another band pass filter after the output pulse to balance the intensity of the two frequency combs. Figure 5(a) shows the corresponding eye-diagram of the ~76 GHz pulses. It is instructive to note that the upper limit of the attainable repetition rate is not dictated by the range of injection locking, but is limited in this case only by the SOA's nonlinearity and

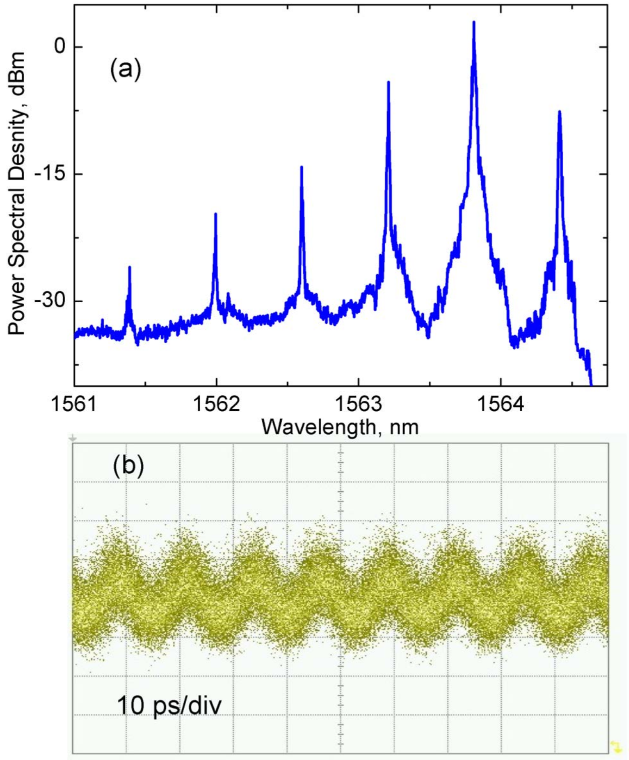

Fig. 5. Measured (a) optical spectrum and (b) eye-diagram of the generated 76 GHz optical pulse.

the instrumentation used for characterization. The bandwidth of the FFL source potentially allows us to injection lock up to a range of a few THz, for pulse generation.

Injection-locking using FFL with narrower comb spacing is more difficult to achieve. This is because of the smaller locking range required to prevent simultaneous (and unstable) locking to multiple comb modes. In our demonstration, we successfully injection locked using a 10 MHz optical frequency comb source (OFCs). We also utilized an external cavity to eliminate the residual modes. To the best of our knowledge, 10 MHz is the lowest spaced OFC that has been successfully injection-locked to date [12]. This capability enables and provides more flexibility for certain applications [10]. However, in the pulse generation case, the repetition rate tuning resolution not only depends on the frequency comb spacing, but also the free spectral range of the main fiber ring cavity. We define the tuning resolution of the beating signal as f_1 and the free spectral range of the fiber ring laser as f_2. The repetition rate tuning resolution for the pulse generation system is $f = f_1 * f_2$. In our experiment, f_1 which equals the repetition rate of the FFL is ~10 MHz, while f_2 is ~23 MHz. Thus, the repetition rate tuning resolution is 230 MHz. In order to have high tuning resolution, f_2 should be equal to or be multiples of f_1. However in order to suppress the residual modes, f_2 also needs to be delineated with respect to f_1 or its multiples. The optical delay inside the cavity can be used to balance these two requirements.

In conclusion, a stable all-optical pulse generation scheme with broad frequency tunability and narrow linewidth is presented in this Letter. The proposed technique is comprised of two main sections: the injection locking section and a SOA-based fiber ring laser section for the pulse-train generation. The injection locking uses a passive mode-locked laser with a relatively ultra-narrow comb spacing of 10 MHz to lock two DFB slave lasers. The low-phase noise injection-locked beating signal is then injected into the fiber ring laser to generate the pulse via gain-induced FWM [9]. Robust and low-phase noise pulse generation was achieved. Pulse generation in the range of 230 MHz to ~76 GHz with a linewidth ~1 Hz is experimentally demonstrated. A higher repetition rate pulse can be obtained with further optimization of the components, including the use of ultra-long SOAs, accurate tuning of the cavity length, and dispersion management.

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