Gigahertz to terahertz tunable all-optical single-side-band microwave generation via semiconductor optical amplifier gain engineering

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We propose and demonstrate a technique to generate low-noise broadly tunable single-side-band microwaves using cascaded semiconductor optical amplifiers (SOAs) using no RF bias. The proposed technique uses no RF components and is based on polarization-state controlled gain-induced four-wave mixing in SOAs. Microwave generation from 40 to 875 GHz with a line-width ~22 KHz is experimentally demonstrated. © 2013 Optical Society of America

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Owing to its ultra-wide bandwidth and low propagation loss in optical fibres, an optical carrier is an optimum platform for microwave generation, processing, and manipulation [1]. Photonic-based microwave generation techniques have been extensively investigated as they enable a vast array of application domains [1,2]. There are immediate unmet needs in applications including broadband wireless access networks, defence systems, satellite communications, and radar, which can all benefit from versatile microwave sources. Each application demands features that are specific to its needs. For example, as one of the main functions of microwave photonics is to be able to effectively transport the microwave signals on optical carriers via optical fibers, single-side-band generation can be a highly desired feature in the domain of telecommunications and radar signal remoting. Radar, wireless communications, and software defined radio applications all require highly tunable microwave signals with extremely low phase noise. As such, there has been a plethora of techniques to generate, manipulate, and process microwave photonics. A combination of optical elements, in conjunction with microwave components, is often deployed to generate high-quality microwave systems.

The main-stream techniques for photonic-based generation of microwave signals can be divided into two categories. One category relies on utilizing direct external modulation of photonic components by a microwave signal to generate microwave signals with excellent frequency stability [3,4]. Another category achieves microwave generation by optical heterodyning techniques of optical sources. This approach permits the largest tuning because two laser sources can be designed to provide significant relative tuning. This technique suffers from relatively higher-phase noise that can be mitigated if feedback is employed for stabilization, which involves complex setups. Techniques to achieve feedback include injection locking [5] and optical-phase lock loop [6]. Another option is to carefully select two longitudinal modes [7] or two wavelengths [8] from a single-frequency laser source. In this case, the frequency tunability is usually restricted by the dual ultra-narrow bandpass filters required inside the cavity.

Recently, a simple yet powerful technique to generate the optical pulse-trains based on gain-induced four wave mixing (FWM) in a semiconductor optical amplifier (SOA) has been demonstrated [9]. The approach allows self-pulsed laser operation with a widely tunable repetition rate. The novelty resides in the fashion by which the repetition rate is tuned, which was carried out by using the beat frequency between two continuous wave (CW) based single-frequency lasers. A unique advantage of this versatile approach is the optical control afforded of the repetition rate, which could be tuned by controlling the frequency difference between the two light sources. This involves no RF source for its operation and significantly simplifies the setup. Moreover, this novel approach is cost-effective and provides the possibility for hybrid integration as it is comprised of semiconductor chips that can be heterogeneously integrated on an Si platform. In this work, through inspiration from the aforementioned pulse-train source, we develop a novel approach to generate single-side-band (SSB) optical microwaves with broad frequency tunability using cascaded SOAs.

The technique of generation can be best explained using Fig. 1, which outlines the principle of the proposed technique for all-optical microwave signal generation. Two linearly polarized single-mode distributed feedback (DFB) lasers are externally injected into the ring laser to modulate the gain of an SOA with their beating signal.

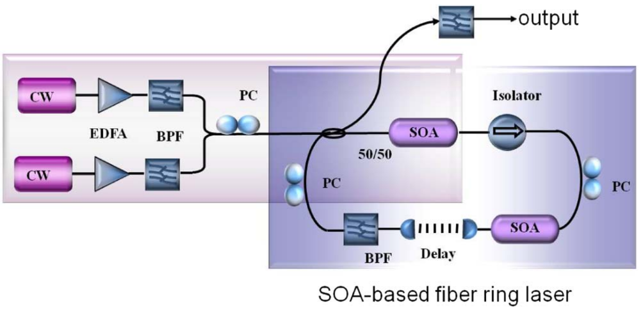

Fig. 1. Experimental setup for photonic microwave generation based on gain-induced FWM. BPF, bandpass filter; PC, polarization controller.

Through controlling the polarization state inside the cavity, the gain profile within the bandwidth of the optical bandpass filter (OBPF) has a linear positive/negative slope that results in CW lasing of the fiber laser cavity at the edge of the OBPF pass band. Thus, when the external beating signal is injected into the fiber loop cavity, only single-side gain-induced FWM will prevail while the other side bands will be rejected by the OBPF.

As can also been seen in Fig. 1, the main fiber ring cavity is comprised of two SOAs [Kamelian nonlinear SOAs & Thorlab boost optical amplifier (BOA)]: the first SOA functions as the gain and modulation media; the second one changes the net gain of the cavity. The first SOA is especially designed for high-nonlinearity with a typical small signal gain of 15 dB at 300 mA current bias. The second SOA provides high net gain with an associated saturation output power of 17 dBm. The isolator ensures the unidirectional propagation of light. The tunable flat-top OBPF has a 3 dB bandwidth of ~6.8 nm centered at ~1560 nm. It is employed to perform wavelength selection of the output and filter the injected beating signal. The polarization controller aligns the polarization state of the lasing mode with that of the injected lasers. Two linearly polarized single-mode DFB lasers are externally injected into the ring laser to modulate the SOA gain, with their beating signal. The central wavelengths of the DFBs in this demonstration are 1552 and 1555 nm. The central wavelength can be precisely tuned in a ~4 nm range using a temperature controller. A 50/50 coupler couples the external pulse train into the fiber ring cavity and out-couples the output pulses.

The source initially operates in a CW mode (i.e., without external injection). The polarization state is carefully chosen and maintained so that the CW source is in a stable lasing state on the right side of the bandwidth of the OBPF. The output of the CW sources is centered at ~1563.5 nm with ~5 dBm output power. By fixing one DFB central wavelength to ~1554.5 nm and tuning the other from 1554.18 to 1547.5 nm, 40 to 875 GHz beating signals are generated. To achieve large-range frequency tunability, two independently tuned DFBs centered at 1549 and 1552 nm are used. The tunability is achieved by the temperature tuning and drive-current tuning. The external beating signal with a power level of 7 dBm is coupled into the cavity. Frequency combs are generated at one side of the lasing frequency. Figure 2(a) shows the corresponding optical spectrum of the optical microwave from 40 to 875 GHz. It is important to note that at 40 GHz the left side band to right side band ratio is ~15 dB. For frequencies lower than 40 GHz, the optical microwave is still generated. However, the microwave signal will switch from SSB to double side band. The signal to noise ratio for 875 GHz microwave is ~17.5 dB, which limits the upper frequency of generated microwave signal. There is a fundamental limit that is determined mainly by the available nonlinearity in the SOA, but in this case it is also limited by the BW of the OBPF used. We note that intensity unbalance exists between the two frequency combs of the generated microwave signal. This can be improved by enhancing the nonlinearity inside the ring cavity or placing a properly designed bandpass filter at the output of the microwave signal. At the output port, a 95/5 coupler followed with one narrow bandpass filter in each arm is used to select the frequency comb of microwave signal. The autocorrelation trace is measured using a second harmonic generation SHG autocorrelator. Figures 2(b)–2(d) show autocorrelation trace of the 40, 375, and 875 GHz optical oscillation separately which confirms the microwave signal generation using proposed scheme.

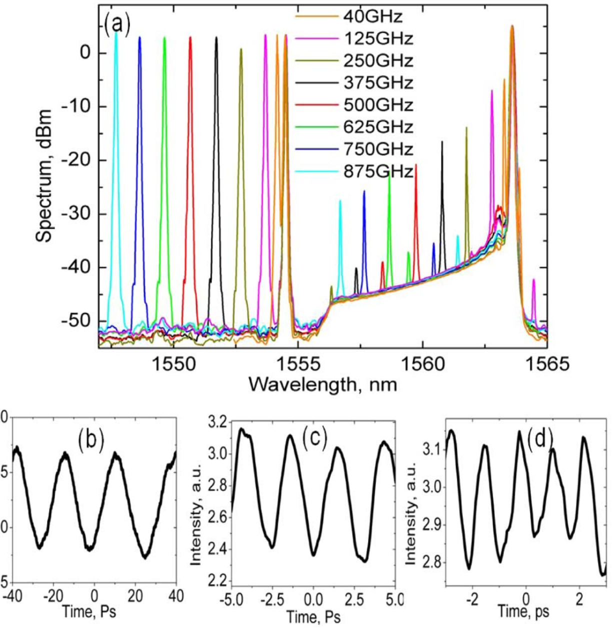

Fig. 2. Measured profiles of spectrum characteristics of the output optical microwave (a) 40–875 GHz with two CW inputs. (b)–(d) Auto-correlation trace of the output of (b) 40 GHz, (c) 375 GHz, and (d) 875 GHz.

To examine the quality of the output microwave signal, we measure the linewidth of the oscillation lines using a recirculation delayed self-heterodyne interferometer (RDSHI) detection method [10]. We first use a narrow tunable bandpass filter to select the frequency comb generated through gain-induced FWM of each microwave signal. Then we send the frequency comb to a RDSHI with a 45 km long fiber delay line and a modulation frequency of 5 MHz. The linewidth of the microwave is measured by a fast photo-detector and electrical spectrum analyzer ESA. The obtained RDSHI power spectrum for the 125 GHz microwave is shown in Fig. 3(b) as a representative example. We use the fifth beat note to evaluate the linewidth with ~0.625 KHz resolution. The RDSHI power spectrum of the fifth beat note is shown in Fig. 3(c) along with the Voigt fitting. It was found from the measurements that the linewdith is ~20.45 KHz (FWHM). The linewidths of all generated photonic microwave signals are characterized. Figure 3(a) shows the measured linewidth versus the frequency of microwave signal. As can be seen, the linewidth of microwave signal from 125 to 875 GHz remains constant and well below 22 KHz. The linewidth of the microwave signal obtained here is significantly narrower when compared with the external injection (the linewidth of the external injection from two DFB is ~10 MHz) and is dictated by the ring laser cavity and the linewidth enhancement factor of the SOA used inside the cavity [11].

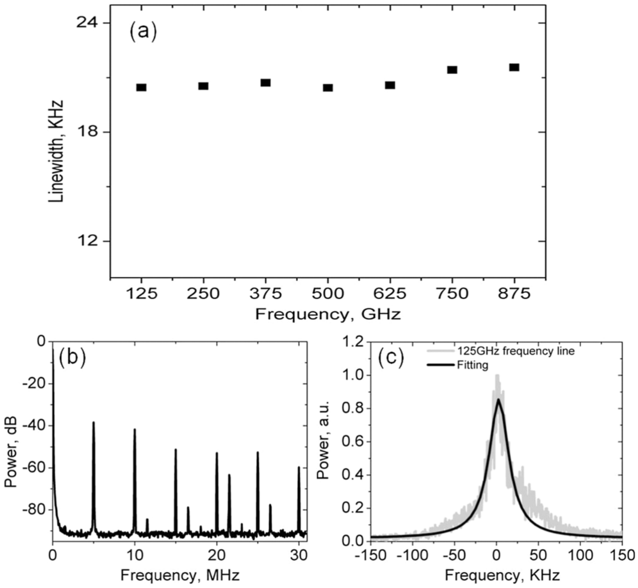

Fig. 3. Phase noise measurement performed using a recirculating delayed self-heterodyne interferometer. (a) Measured linewidth versus the microwave frequency. (b) Broad view of the recirculation delayed self-heterodyne interferometer (RDSHI) power spectrum. (c) RDSHI power spectrum of the 125 GHz frequency line along with the Voigt fitting.

Obtaining direct measurements of frequency tunability and stability of the generated microwave signal directly required instrumentation that was not available at the time. We are able however, to estimate the tunability and stability from the low-frequency microwave generation since the generation scheme is unchanged. To evaluate the resolution of the frequency tunability, a double-side band microwave at 471 MHz is first generated. The broad view of the power spectrum is shown in Fig. 4(b). Then by fine tuning the frequency of the beating signal by continuously tuning the DFB drive current, the microwave frequencies with tuning resolution ~21 MHz is obtained. The power spectra of the microwave signal are shown in Fig. 4(a). It should be noted that the resolution is determined by the fundamental mode spacing of the main ring cavity. It is equal to this cavity mode spacing. Thus, by increasing the main cavity length, we can achieve higher-frequency tuning resolution. However, there is a trade-off involved: the linewidth of the external injection from two DFB is ~10 MHz with ±5 MHz frequency fluctuation, so to obtain stable and single-mode side-band operation, the fundamental mode spacing of the main ring cavity should also be larger than 20 MHz, which is the resolution limitation.

To examine the stability of the output microwave signal, measurements are taken at a time interval of 12 min for different microwave frequencies (i.e., 541, 990 and 1.53 GHz). The measured microwave frequency is shown in Fig. 5(a). As we can see, in the 12 min interval, the microwave frequency remains relatively stable. The adjacent longitudinal mode hopping results in frequency drift ~ ±22 MHz. From this measurement, we anticipate that the fluctuation is mainly introduced and is dictated by the external modulation. Thus, we predict that this value is nominally unchanged for the

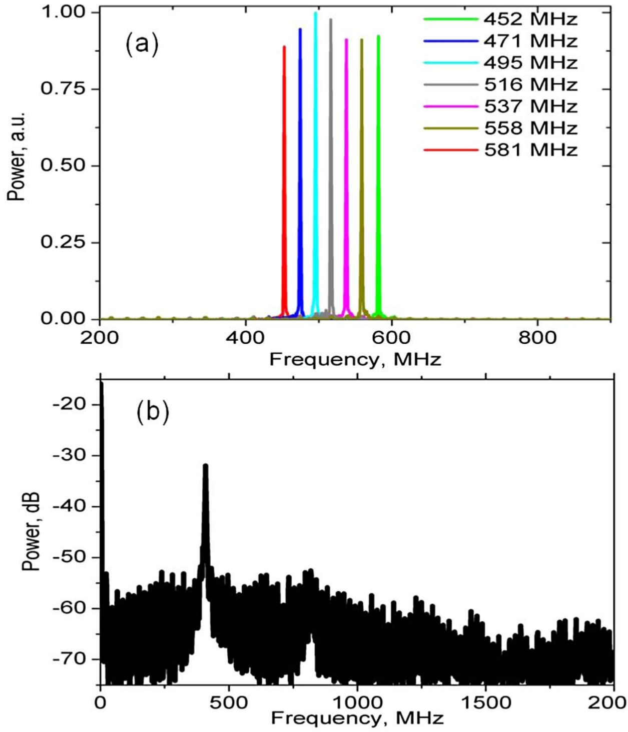

Fig. 4. Resolution of tunability. (a) Power spectra of the microwave signal at the output of the photodetector. (b) Broad view of power spectrum of microwave at 471 MHz.

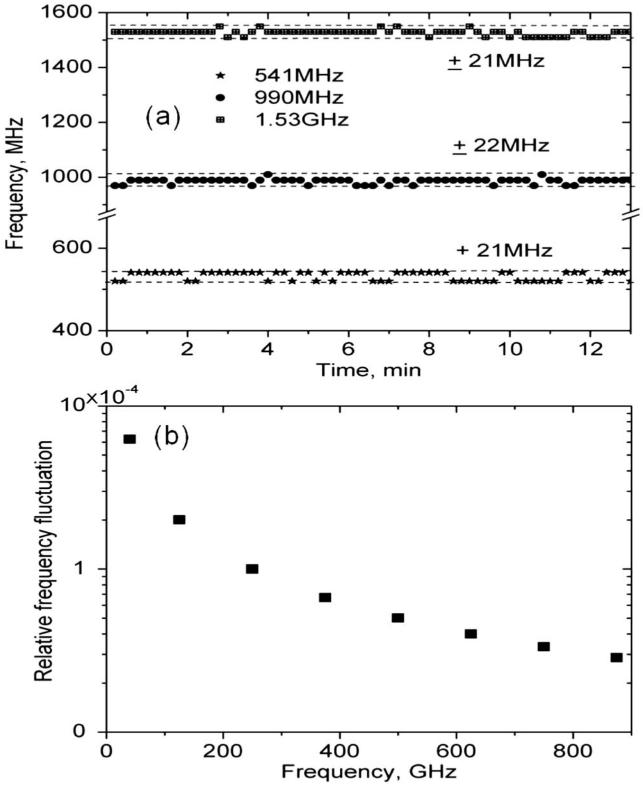

Fig. 5. Microwave stability measurement. The relative frequency fluctuation is defined as the ratio. (a) Frequency fluctuation versus time. (b) Estimated frequency fluctuation ratio versus frequency. The relative frequency fluctuation is defined as the ratio of the frequency fluctuation to the center microwave frequency generated.

entire range of microwave frequency (i.e., 40–875 GHz). Due to the wide frequency range obtained by our sources, we define a relative frequency fluctuation figure of merit. The relative frequency fluctuation is defined as the ratio of the frequency fluctuation to the center microwave frequency generated. Figure 5(b) shows the estimated relative frequency fluctuation versus the microwave frequency. Relative frequency instability under a factor of $\sim 7 \times 10^{-4}$ is estimated. In the THz regime this relative fluctuation drops by at least one-order of magnitude as can be seen in Fig. 5(b). By decreasing the length of the main cavity, we can enlarge the fundamental mode spacing which will result in enhancing the stability. We anticipate that with further integration, the instability of the proposed technique will by highly improved. However, one should consider the trade-off between the resolution and stability for further main ring-cavity design.

In conclusion, a novel photonic microwave generation scheme with broad frequency tunability and narrow linewidth is presented in this Letter. The proposed technique is based on gain-induced FWM in cascaded SOAs. Photonic microwave signals with frequency from 40 to 875 GHz are demonstrated with linewidth down to 22 KHz. The microwave frequency tuning resolution of 21 MHz is achieved. We estimate the frequency instability under a factor of $\sim 7 \times 10^{-4}$. The proposed technique has no upper bound of microwave frequency generation. Higher-frequency microwave signals 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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