A widely tunable, low phase noise microwave source based on a photonic chip

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Spectrally pure microwave sources are highly desired for several applications ranging from wireless communication to next generation radar technology and metrology. Additionally to generating very pure signals at ever higher frequencies, these advanced microwave sources have to be compact, small weight and low energy consumption to comply with in-field applications. A hybrid optical and electronic cavity, known as an opto-electronic oscillator (OEO), has the potential to leverage the high bandwidth of optics to generate ultra-pure high-frequency microwave signals. Here we present a widely tunable, low phase noise microwave source based on a photonic chip. Using on-chip stimulated Brillouin scattering (SBS) as a narrowband active filter allows single mode OEO operation and ultrawide frequency tunability with no signal degeneration. Furthermore we show very low close-to-carrier phase noise. This work paves the way to a compact, fully integrated pure microwave source.

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Ultra-pure microwave signals are essential for radar technology to precisely measure the distance of objects, as reference clocks for communication networks or data carriers for wireless communication. Especially with mobile communication being omnipresent in every-day's life the demand for bandwidth in wireless communication schemes is steadily increasing and therefore microwave sources which are able to generate stable high-frequency microwave signals (several tens of GHz) in a small form factor are needed. The generation of high frequency microwave signals as data carriers, however, is challenging when done electronically, because the losses are increasing with higher frequencies and electronic systems are known to suffer from parasitic electromagnetic interferences. Microwave photonics, in particular integrated microwave photonics, offers great potential to overcome these barriers and provides solutions for problems known to be notoriously challenging in electronics [1]. A good example is an optoelectronic oscillator (OEO), which harnesses optics to generate ultra pure microwave signals [2–5]. It was shown that these oscillators - consisting of a cavity which is half optical and half electrical - can be used to generate pure single frequency microwave sources with very low phase noise [6]. However, most of the demonstrated OEOs did not take advantage of the large bandwidth optics is able to provide. The main reason for this limitation is the fact that the OEO relies on a narrow-band filter to ensure that only one cavity mode is oscillating. This filter needs to fulfill quite stringent requirements: on the one hand it needs to operate in the range from GHz to tens of GHz, and on the other hand exhibit very narrow bandwidth in the orders of a few MHz or less. This filter can be implemented in either the optical or the electrical part of the cavity. However, electrical filter with the above-mentioned requirements usually have a high insertion loss (typically around 10 dB) and lack tunability. The high loss also degrades the noise performance of the OEO as it requires reamplification of the signal. Similar problems occur for narrow-band optical filters, such as e.g. high finesse Fabry-Perot cavities.

Here we show the first photonic-chip based OEO employing a narrow-band active Brillouin filter. Besides being chip-scale size with the potential to be fully-integrated, the Brillouin filter provides gain to the cavity and therefore no additional reamplification to compensate filter losses is required, allowing low phase noise (< 100 dBc/Hz at 100 kHz offset frequency). The active Brillouin filter also allows ultra-wide tunability of the generated microwave signal without any degradation of performance (in our demonstration up to 40 GHz). Harnessing the large Brillouin gain of chalcogenide rib waveguides allows to employ the Brillouin filter in a short length [7–9], which makes this demonstration the first truly single mode OEO

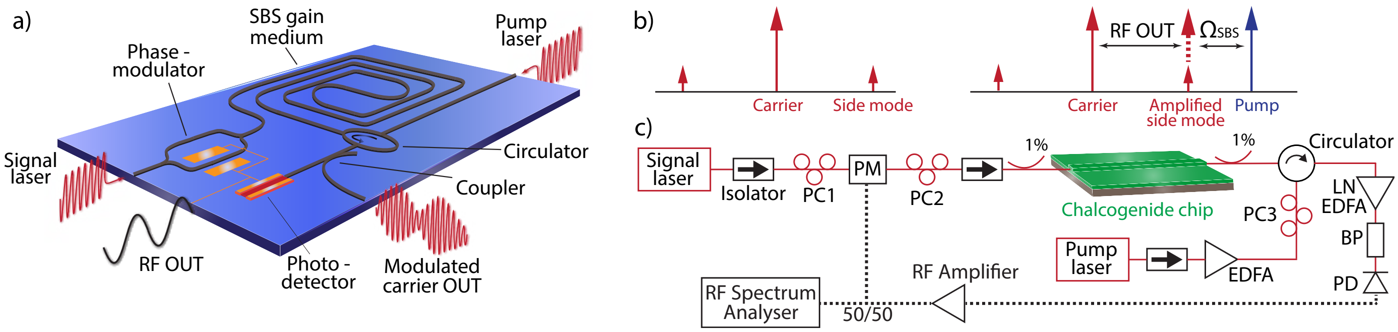

Fig. 1. a) Artist's impression of a fully integrated OEO. b) Basic principle of the SBS-based OEO. The narrow band Brillouin gain amplifies one of the side modes converting the phase modulation into an amplitude modulation which can be detected at a photodetector. c) Experimental setup of the chip-based OEO. PC1-3: Polarisation controller; PM: Phase modulator; EDFA: Erbium-doped fibre amplifier; LN EDFA: Low-noise EDFA; BP: Bandpass filter; PD: Photodetector.

based on a Brillouin filter. Therefore the stability of the OEO is increased as there is no mode-hopping occurring. Relying only on very few components - which all have been demonstrated on-chip already [10–17] - the design and construction of a fully integrated OEO is feasible (see Fig. 1a). Therefore this work paves the way to a cost effective, due to scalability in the fabrication process, small-footprint ultra-pure microwave source.

The basic principle and the experimental setup of the chip-based OEO is depicted in Fig. 1b) and 1c), respectively. A signal laser, a distributed feedback (DFB) laser, passes through a phase-modulator and is coupled to ~~the~~ a 6 cm long highly nonlinear chalcogenide rib waveguide with a cross-section of 850 nm × 2.6 μm. A second DFB laser serves as a pump and is coupled from the opposite side to the chip, generating the narrow-band SBS response. SBS describes a nonlinear interaction between an optical pump ω_{pump}, an acoustic wave Ω_{SBS} and an optical Stokes wave ω_S. In this process the optical Stokes wave experiences exponential gain [18]. Initially the phase modulator gets just seeded by white noise. However, as SBS provides a narrow-band gain inside the cavity one of the side modes gets amplified. The bandwidth of the SBS gain is around 30 MHz in chalcogenide glass [7], which is significantly wider than the linewidth of the used pump laser (sub-MHz). The radiofrequency (RF) beat frequency gets fed back into the phase modulator, and above a threshold the OEO starts oscillating at this particular frequency, which is given by $\omega_{OEO} = \omega_{pump} - \Omega_{SBS} - \omega_{carrier}$. As only one side mode gets amplified the phase modulation is converted into amplitude modulation, which can be detected at a photodetector. Therefore the Brillouin active filter allows the use of a phase modulator instead of the intensity modulator commonly used in OEOs. A phase modulator does not require a DC bias, which would otherwise need to be controlled with a low-noise phase-lock loop. It also has lower insertion loss, further reducing the cavity loss and thus the noise of the OEO signal.

An optical spectrum of the built OEO is presented in Fig. 2. It shows the OEO in open loop operation with 10 dBm RF seed power from an RF signal generator at the phase modulator. One can see that SBS amplifies the upper side mode leading to 12 dB difference in optical power of the two side modes, matching the power of one side mode with the carrier power. In the right corner of Fig. 2 one can see the residual SBS pump, backreflected from the facet of the chip. In our measurement an optical bandpass filter is used to remove this backreflection

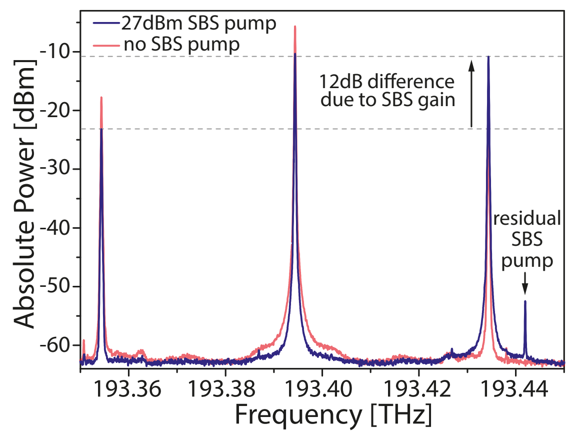

Fig. 2. Optical spectrum of the OEO in open-loop operation with 10 dBm RF seed power at the PM. The upper side mode gets amplified by SBS leading to a 12 dB difference in the side mode power.

to avoid any detrimental beat signals. We want to clarify that the optical bandpass filter in the setup shown in Fig. 1c) serves the only purpose to suppress this backreflected SBS pump laser signal. The backreflected pump signal, however, could be strongly suppressed by moving to a fully integrated chip, using wire bonding [19] or photonic chips with tapers and anti-reflection coatings [20]. The oscillating microwave mode of the OEO is shown in Fig. 3 at a frequency of around 40 GHz. The total span of Fig. 3 is only 250 kHz showing the narrow linewidth character of the OEO. In Fig. 3b) we show the ultra wide tunability of the SBS-based OEO. This is one of the key advantages of photonics compared to electronics - there is no degradation in the signal when going to higher frequencies. Whereas the high quality microwave output is a typical characteristic of an OEO, the wide tunability is a specific feature of the dual pump SBS based setup. Here the OEO output frequency can be simply changed by tuning the frequency of the carrier laser relative to the SBS pump laser. The spectra were measured in 5 GHz windows and stitched together to obtain better resolution. We want to emphasize that there were no other cavity modes oscillating over the whole span, besides the main OEO output mode. Here we show tunability up to 40 GHz, which is only limited by our equipment

- namely the modulator and the photodetector. However it was shown that all-integrated modulators can exceed modulation speeds of 100 GHz [12–15] and recent research on graphene photodetectors predicts operational speeds of up to 500 GHz [21].

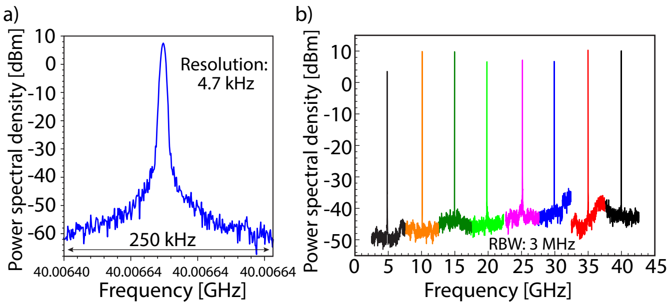

Fig. 3. a) RF spectrum of the OEO output signal at around 40 GHz. b) Ultra-wide tunability of the OEO output signal. The tuning is achieved by tuning the pump laser frequency relative to the carrier frequency (RBW: Resolution bandwidth).

The most important figure of merit for microwave sources is its stability, which can be quantified by measuring the phase noise of the source. This gives a direct indication of the stability and purity of the source. Fig. 4a) shows the measured phase noise of our SBS based OEO and compares it to a high-range commercial microwave source (Agilent N5183A). The phase noise is measured using an microwave spectrum analyser (Agilent E4448A).

In the range up to 1 MHz we see no detrimental cavity side modes present. This is a result of the high SBS gain on-chip enabling a short cavity (in total about 25 m), which results in a truly single moded OEO with great stability and no detrimental mode-hopping. Furthermore, we see that the phase noise of the OEO at close-to-carrier frequencies is orders of magnitude lower than the Agilent microwave source. The flat and low noise of the OEO at low frequencies is a result of the noise properties associated with SBS. At low frequencies (below 10 kHz offset frequency), SBS was reported to generate an optical signal with unusual relative intensity noise (RIN) characteristics. At low offset frequencies (< 10 kHz) the SBS signal RIN is decreasing at about an f^2 rate [22], whereas the RIN of optical signals usually increases at f^{-1} rate or is white f^0. As white RIN produces the typical f^{-2} OEO phase noise [2], SBS RIN (with f^2 slope) is expected to produce flat phase noise, which is perfectly in line with our experimental observations.

Furthermore it is known that operating the SBS filter/amplifier in saturation leads to an improved noise performance [23]. Operating at relative high pump powers (around 23 dBm) also provides the maximum gain for the selected sideband mode, giving the steepest response of the active Brillouin filter. It is worth mentioning that the photocurrent from the photodiode of our OEO was high, about 20 mA, making optical RIN the dominant contribution of the noise [2]. This is opposed to most OEO demonstrations, where thermal or shot noise was the limiting factor. Besides a slight bump in the phase noise curve at around 10 kHz the phase noise of the OEO is below the commercial microwave source.

Fig. 4b) compares the noise performance of the OEO at 40 GHz and at 10 GHz. It was shown previously [2] that the phase noise of an OEO does not depend on the operation frequency, which

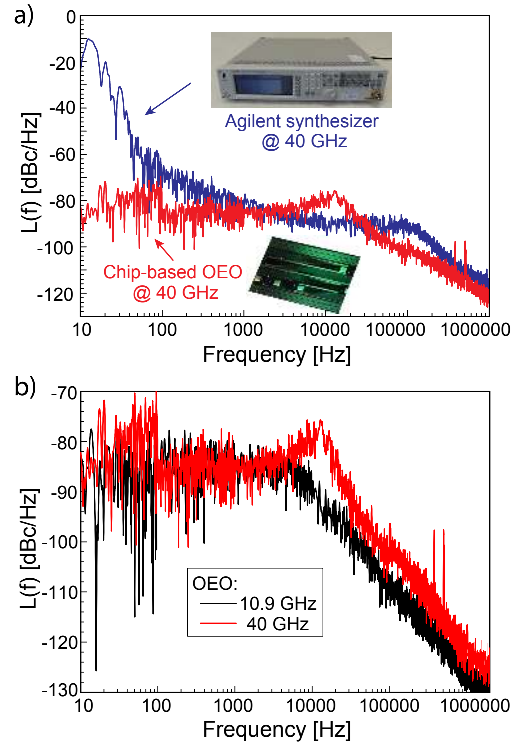

Fig. 4. a) Comparison of the phase noise performance of the OEO (red curve) and a high range commercial RF synthesizer (blue curve). b) phase noise performance of the OEO at different RF frequencies. Note the slightly worse noise performance at 40 GHz is due to limitations in the used RF components.

we also observed experimentally for frequencies up to 30 GHz. Beyond this frequency, we saw slight signal degradation due to the limited bandwidth of the used RF components. The modulator, amplifier as well as the photodetector were operated at their frequency limit. The phase noise at 40 GHz (limited by the used RF components) and 10.9 GHz (typical performance up to 30 GHz) is shown in Fig. 4b). However, these limitations can be overcome with better components and therefore the noise performance of the OEO could be further improved at high frequencies.

We demonstrated a chip-based highly pure microwave source harnessing SBS. We show that the noise performance of our on-chip OEO is comparable with high-range commercial microwave sources. The strong photon-phonon interaction in chalcogenide waveguides enabled us to utilize high Brillouin gain in a short length scale, realising the first single-mode OEO based on SBS. Furthermore replacing the commonly used electronic filter in the OEO cavity with an active SBS filter enabled ultra-wide tunability of the OEO output frequency.

This work paves the way to more compact stable microwave sources. As the whole setup can be integrated on one photonic chip (Fig. 1a) there is great potential to leverage existing nano- and microfabrication facilities with great advantages concerning costs and scalability. A chip-scale source of highly pure microwaves would have a big impact on applications where the size and weight are key demands: such as mobile communication and on-field radar applications. An all-integrated OEO (Fig. 1a) could be interfaced with further photonic components using wire bonding [19]. Additionally to the microwave output an OEO is also able to output the microwave signal modulated on an optical carrier. Therefore it could be used directly in microwave photonic circuits without the need of additional conversion/modulation or be transmitted as radio over fibre signal.

The chip depicted in Fig. 1a) relies only on very few components - of which all are already demonstrated in all-optical chip-scale platforms. Fast photodetectors are available on chip [10, 11] and are steadily improving concerning conversion efficiency and speed. Several different modulators - based on graphene, plasmonics or hybrid organic structures - were also demonstrated on chip recently [12–15]. These on-chip modulators and photodetectors do not only have a very small footprint but also offer operation speeds not seen in commercially available products today. For the SBS waveguide one could either think of a hybrid chalcogenide-on-silicon structure or use silicon waveguides, as Brillouin net gain in silicon was demonstrated recently [17]. Chip integrated isolators or circulators, however, are notoriously challenging [24]. In recent years there was a lot of progress and there are demonstrations with sufficient isolation between the respective ports [16, 25]. On the other hand our concept of an all-integrated OEO does not rely on the circulator - a simple coupler combined with a bandpass filter would also work [26, 27]. Both are standard components in photonic chips today.

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