Ultra-wideband Photonic VCO and Synthesizer

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Abstract—A novel low phase noise photonic voltage-controlled oscillator is presented and synthesizer. It is capable of operating at any center frequency from 1-110 GHz, tunable across several decades. The photonic VCO’s phase noise is superior to that of existing technologies for applications beyond 60 GHz; it will extend the capability of existing applications as well as open new ones.

Keywords—Voltage controlled oscillator, receivers, ultra-wideband radar, millimeter wave radar, phase noise.

I. INTRODUCTION

There has been increasing recent interest in extending the frequency band of operation in many RF applications such as communication systems, radar, sensors and receivers. The advent of 5G, and emergence of 6G communication paradigms is extending the frequency from single digit GHz range all the way to 100 GHz and beyond. Civilian radar applications related to, for example, investigation of cloud and water moisture in the atmosphere also require operation at 170 GHz and 250 GHz [1]. Similarly, receivers for military communications including software defined radio are also migrating to higher frequencies in the V and W-band.

With this backdrop, the task of generating highly spectrally pure carriers in these segments of the frequency spectrum has become quite challenging. This is because highly spectrally pure sources used as carriers or local oscillator (LO) have traditionally been derived by multiplying the frequency of a quartz or similar low frequency oscillators in several steps to reach the frequency of interest. The degradation of the noise governed by 20 log N, where N is the multiplication factor, is well known and is a limiting factor for many of the applications.

Other technologies such as DRO, which operates at a higher frequency than the quartz oscillator, also typically are limited in spectral purity beyond Ka-band.

Achieving wideband tunability is yet another challenge that adds to these limitations in the millimeter wave frequency bands. While technologies such as YIG offer a fairly wide tunability range at lower frequencies, they become essentially less than suitable for higher frequencies with respect to spectral purity and also impose limitations on size, weight and power budget. Nevertheless, the current practice for achieving ultra-high frequency, tunable sources start with a high performance, relatively high frequency DRO or similar oscillator and use several stages of frequency multiplication, directly or via phase lock loops. This approach has already produced commercial synthesizers that can reach frequencies above 400 GHz. Nevertheless, the phase noise performance of these equipment is subject to the limitations imposed by the 20 log N relation between noise and frequency multiplication, so that the noise of the synthesizer is frequency dependent and larger frequencies feature higher noise. IMPATT diodes, CMOS and Gunn Oscillators, on the other hand, can directly generate signals at high frequency, but lack wide tuning range and are very noisy at high frequencies. Here we report on an ultra-wideband photonic oscillator capable of generating signals at frequencies as high as 110 GHz, with unprecedented low phase noise. Details of the oscillator, which can function as a frequency synthesizer for 110 GHz signals are presented below.

II. ULTRA-WIDEBAND PHOTONIC VCO

Photonic technology has been addressing many of the challenges mentioned above and highly spectrally pure sources up to Ka-band frequencies (and in a few examples higher) have been realized by taking advantage of its special features. These include low waveguide loss and automatic filtering of the frequency as a result of the bandwidth of the photodetector, and linear and nonlinear properties of optical resonators. These features have been utilized to assemble special opto-electronic oscillator loops [2], which are now reported in various configurations in the literature [3], and ultra-high Q optical micro-resonators with Kerr nonlinearity [4].

The simplest approach for generating RF frequency with photonics is the use of two lasers with frequencies (wavelengths) separated by the targeted value to beat on a photodetector and produce the desired RF frequency. This simple approach takes advantage of the fact that a photodetector is a quadratic detector, and thus can serve as a photo mixer. Furthermore, the frequency difference between the two lasers can be readily adjusted with the use of tunable lasers to achieve operation at a wide RF frequency band.

Despite its simplicity this approach is not in widespread use for generation of highly spectral pure RF signals. This is because the photodetector is subject to the limitations imposed by the 20 log N relation between noise and frequency multiplication, so that the noise of the photodetector is frequency dependent and larger frequencies feature higher noise. Here we have assumed the worst case where the noise in the two lasers is not correlated. Therefore, to generate a 100 GHz signal characterized with phase noise $L_{RF} = -140$ dBc/Hz at 10 MHz, the optical signal should have phase noise $L_{laser} = -143$ dBc/Hz at 10 MHz. Such a low value of noise is not achievable with lasers that are compact and easily tunable over a wide frequency range.
We have previously demonstrated an ultra-low noise semiconductor laser based on optical injection locking it to an ultra-high Q (> $10^9$) crystalline optical whispering gallery mode (WGM) resonator [5]. Owing to their very large Q values, the bandwidth of these modes is quite small (in a few hundred kHz range) for laser emission at about $2 \times 10^{14}$ Hz. The narrow bandwidth provides an effective means for filtering the noise of the laser. We realize this function through the process of self-injection locking of the laser to a mode of the resonator, whereby a small amount of light back scattered from the resonator into the laser automatically injection locks the laser to the WGM. The back scattering of light is through the process of Rayleigh scattering and occurs due to imperfections in the resonator material and in surface smoothness. This approach has demonstrated reduction of the noise of a semiconductor laser operating at 1550 nm by as much as 60 dB, as shown in Fig. 1.

![Fig. 1 scheme of a semiconductor Distributed Feedback laser (DFB) locked to a WGM resonator (left panel). Here the laser light is coupled evanescently to a WGM of the resonator via a coupling prism. Some of the light circulating in the WGM are reflected back to the laser to injection lock it. The light out of the resonator is collimated by a lens (on the right) as the low noise laser output. The noise laser is shown as the power spectral density of the phase noise in the right panel, which also shows the reduction of 60 dB when the laser is injection locked.](image)

We performed an experiment using a pair of lasers based on the architecture depicted in Fig. 1. The lasers were assembled in a configuration whereby the frequency of one of them could be tuned across 110 GHz. The lasers beams were then combined and introduced to a fast photodetector (Finisar XPV4121R). The output of the photodetector was then coupled to a spectrum analyzer while the frequency of the tunable laser was changed to produce signals at 10 GHz intervals, ranging from 1 to 110 GHz. Fig. 2 shows the result of this experiment. It is clear that any desired frequency in this range could be produced by properly adjusting the output frequency of the tunable laser. In this experiment both lasers could be tuned individually, or together. Tuning was accomplished by changing the current of the laser, the temperature of the laser, or the combination of the two. Meanwhile, each laser was kept injection locked to the resonator when the frequency of interest was achieved.

The phase noise of this wideband signal generator was also measured by two approaches. First, we used OEwaves’ RF Phase Noise Test System (OE8000) to directly measure the phase noise of signals at 6, 9, 10 and 11 GHz, shown on the left panel in Fig. 3. As can be seen, the phase noise plots overlap confirming the noise at all these signals remains unchanged. To get an estimation of the phase noise of the output at higher frequencies we performed optical phase noise measurements of the tunable laser using OEwaves’ Optical Phase Noise Test System (OE4000). Here again, the phase noise at all frequencies remains the same (Fig. 3, right panel), again confirming the expected absence of multiplied phase noise that is a feature of the photonic approach, as mentioned above. Direct RF phase noise measurements at W-band show agreement between the predicted noise calculated from optical noise summation according to $L_{\text{RF}} = 2L_{\text{laser}}$ relationship and the actual RF noise. This data will be published elsewhere.

![Fig. 2 Signals generated by the Photonic VCO. The noise floor shown is limited by the Keysight UXA RF spectrum analyzer.](image)

![Fig. 3. (a) Phase noise of the output of the VCO at various frequencies. Note that the power spectral density of the noise at Fourier frequencies below about 50 Hz is larger than zero. This is a feature of the definition of the single sideband power spectral density, which exceeds zero when phase variations exceed about 1 radian [6]. (b) Optical phase noise of the tunable laser as it is tuned over a wide frequency range showing essentially no change in the noise level.](image)

This system clearly realizes an ultra-wideband source of RF frequency from essentially DC to 110 GHz. It is important to point out that the upper limit of the frequency is set by the bandwidth of the fast photodetector. Photodetectors with bandwidth up to 450 GHz have been demonstrated, so in principle our architecture comprised of the two ultralow noise lasers can produce frequencies up to that value. Note that while the efficiency of a photodetector as measured by the ratio of the input optical power to the output RF power is frequency dependent, the output noise of the detector is not impacted by the change in frequency within the operating bandwidth.

### III. Opto-Electronic Locking

The photonic signal source as described above is free running. However, the lasers are designed with the temperature of the WGM resonator controlled at a fixed value to keep the center frequency of the WGM, and therefore the laser frequency, fixed. The two lasers are also incorporated in a package and their proximity ensures they experience the same
frequency reference. We have assembled such a locking scheme and a PLL to lock the frequency difference of the two lasers to the low bandwidth photodetector can be used, in conjunction with drift, this beat will change in frequency. Thus, the output of the photodetector belonging to laser 2. When the two lasers are separated by a frequency smaller than the bandwidth of the photodetector, which produces a signal due to laser 1 and laser 2. This output is subsequently fed to a wideband photodetector. Various free standing micro-optical components such as lenses, beam splitters, etc. are assembled to accomplish the function. The overall dimensions of the packaged VCO are 5 x 4 x 1 cm. The VCO is connected to an electronic board (not shown) that incorporates the laser drivers and other ancillary electronics. The output of the VCO is accessed by two mm connectors shown on the side of the package.

We have devised an opto-electronic system for locking the frequency output be kept locked to an external clock or frequency reference. This can be readily achieved at a fixed frequency less than about 30 GHz by employing a digital PLL with an internal (or external) quartz oscillator, or a rubidium clock. We employed both these schemes and successfully locked the signal source at 10GHz and 28 GHz directly to a quartz and again to a rubidium reference to a digital PLL. The phase noise of the output of the oscillator reflected the noise of the reference within the locking bandwidth, which in this experiment was about 100 kHz. Above that Fourier frequency, the phase noise exhibited the noise of the unlocked oscillator, which reached -135 dBC at 1 MHz offset and -150 dBC at 10 MHz. To extend the locking capability to higher frequencies up to the detector limit of 110 GHz, a different approach is required.

We have designed and demonstrated a photonic signal generator for producing highly spectrally pure signals between 1 and 110 GHz. We have shown that the spectral purity of signals generated with this oscillator is independent of the output frequency. Finally, we have demonstrated an opto-electronic scheme to lock the photonic signal generator’s output to an RF reference oscillator or clock at any desired frequency. In this manner, we have realized a high performance, compact, synthesizer for 1-110 GHz frequency range, a range limited by the BW of the photodetector used. As commercial PD’s become available with higher bandwidth, this architecture naturally translates to frequencies of 450 GHz and beyond.

REFERENCES