The Opto-Electronic Oscillator (OEO): Review and Recent Progress

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***Abstract*—This paper reviews developments over the past two decades related to the Opto-Electronic Oscillator (OEO). Various approaches for realization of the OEO architecture are discussed. Recent advances related to generation of spectrally pure signals with a compact configuration of OEO, based on optical whispering gallery mode (WGM) resonators are discussed. Finally, based on the current development, future versions of the OEO, which combine the optoelectronic feedback loop with a Kerr comb frequency generator made with a crystalline WGM resonator, are mentioned.**

I. INTRODUCTION

Spectrally pure and frequency stable microwave and mm-wave reference signals have widespread applications in diverse fields of science and technology ranging from metrology to communications, sensing, and radar. The need for high performance sources in this spectral domain is growing at an increasing rate in response to advances in technology related to radio astronomy, mm-wave metrology, and high rate data transmission networks with associated wider bandwidth requirements. The traditional approach for generating spectrally pure signals relies on multiplication of lower frequency signals generated with high performance quartz or surface acoustic wave (SAW) oscillators, or direct generation using high quality factor (Q) microwave and mm-wave resonator oscillators, but these approaches have inherent limitations. In the case of multiplied signals, the multiplied noise of the high performance oscillator at 20 log N, with N the multiplication factor, limits achievable performance; in the direct generation scheme, the high Q cavity is bulky, highly sensitive to environmental perturbations, and for the highest performance requires cryogenic cooling, thus limiting applications where size, weight, and power are restricted.

II. THE OPTO-ELECTRONIC OSCILLATOR (OEO)

A. General Scheme

In the last fifteen years, generation of spectrally pure microwave and mm-wave signals has been achieved using optical schemes. The most widespread approach is based on the opto-electronic oscillator (OEO) where high Q optical cavities with extremely low loss are used with opto-electronic feedback loops. The generic OEO consists of a light source (usually a laser), light modulator, optical cavity, and a photodetector; the output of which is fed back to the modulator to achieve a closed loop configuration (see Figure 1). This feedback loop can generate self-sustained oscillation if its overall gain is larger than the loss, and the waves circulating in it add up in phase. The former requirement can be met with insertion of gain in the loop and, the latter, by controlling the phase. Since the loop can support waves circulating once, twice, …n-times, the oscillator is fundamentally multi-mode, with the mode spacing determined by the free spectral range of the cavity. By adding a filter in the loop with a prescribed center frequency ν, the output of the oscillator can be obtained at that frequency. In this way, any frequency supported by the bandwidth of the components can be generated. The close-to-carrier phase noise of the OEO is fundamentally determined by the Q of the optical resonator, while its white noise floor is determined by the shot noise of the optical power on the photodetector. In practice, the noise is ultimately limited by the 1/f noise of the amplifier in the loop, and the 1/f noise of the photodetector.

The power of the OEO architecture is in its flexibility as it can be configured in a variety of ways with different optical and electrical components to optimize the performance. The gain, the filter, the phase shifter can be placed either in the optical segment or the electrical segment of the loop. The light source can be of any suitable type, including a laser or a source of amplified spontaneous emission (ASE); modulation of light can be achieved directly with the current of the laser, or with an external modulator. The signal can be generated with phase, amplitude, or polarization modulation. The high Q cavity can be a Fabry-Perot, a whispering gallery mode optical resonator, or a long fiber delay with an equivalent $Q = \pi \tau \nu_0$, where ν_0 is the oscillator frequency, and τ is the delay given by nL/c, with L the length of the fiber, c the speed of light, and n the index of refraction of the fiber. The operation

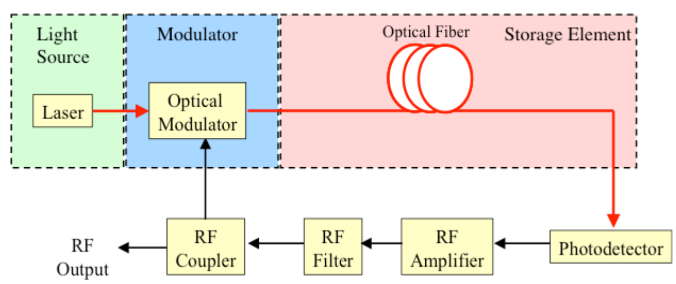

Figure 1 Generic configuration for Opto-Electronic Oscillator (OEO)

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frequency can be fixed by a fixed filter or tuned by changing the RF filter's center frequency, or the cavity's "optical length" through controlling dispersion, or the wavelength of the laser. Finally, even the light source can be a laser external to the loop, or a source produced by placing gain in a second optical loop that is coupled to the electrical loop through the modulator, which is shared by both loops. This latter configuration is known as the coupled opto-electronic oscillator or COEO.

An attractive feature of the OEO architecture is that its noise can be accurately modeled with analysis and with numerical simulations. In the original paper describing the OEO, a model for the noise of the oscillator was presented [2]. This model has been modified by various authors to include the effect of noise in the components such as amplifiers and detectors on the overall spectral purity [4]. Noise models based on Laplace transform formalism and Langevine equations have also been developed [23]. A recent paper has studied the optical noise associated with the use of the fiber in the loop, and experimentally verified what has been previously asserted regarding the influence of Rayleigh scattering and Brillouin effect [22].

Variations of the OEO architecture by several research groups around the world have been employed to generate high performance microwave and mm-wave signals. In the fiber based OEO, the length of the fiber is related to the Leeson frequency given by:

$$f_L = \frac{\nu_0}{2Q}$$

where ν_0 is the frequency of the oscillator. A 16 km long fiber was used to obtain the highest achieved spectral purity of -163 dBc/Hz in a 10 GHz free-running oscillator, at 7 kHz from the carrier [4]. This performance was limited by the flicker noise of the photodetector the loop. One of the features of a fiber delay is that oscillations at frequencies that are multiples of the fundamental frequency associated with the length of fiber (the analog of longitudinal modes of a laser resonator) are also supported. This multi-mode oscillation, mentioned above, can be suppressed if the bandwidth of the filter in the loop is narrow enough so that only a single mode of oscillation survives in the loop. Such a narrow-band filter, however, is not practical, especially when the length of the fiber is long and the operation frequency is in the microwave and mm-wave range. For example, for a 4 km length of fiber the frequency associated with these modes is about 90 kHz; a filter with this bandwidth is hard to realize at frequencies above a GHz.

One approach to mitigate this problem is to utilize optical (instead of electronic) filters in the OEO. This scheme is particularly attractive since Fabry-Perot cavities and whispering gallery mode (WGM) optical resonators can have narrow bandwidth. A low noise OEO has been recently demonstrated with a Fabry-Perot as a filter in the optical loop [5]. A 39 GHz OEO utilizing a WGM resonator as an optical filter has also been demonstrated [6]. Another approach for reducing the amplitude of unwanted modes surviving the filter bandwidth and appearing as "supermodes" in the phase noise spectrum is to use multiple lengths of fiber as an optical filter [7]. These extra loops essentially represent a finite impulse response filter. Such an approach was recently somewhat modified to achieve the overall filtering effect in optics, rather than in combination with the electrical loop [8]. Finally, an OEO utilizing an atomic transition in rubidium was also demonstrated; this oscillator was designed to also achieve high stability of operation derived from the atom [9].

A limitation of multi-loop approach is that filtering is best accomplished when the two fiber lengths are different so that the FSR related to each length is at a proper ratio to ideally provide only a single mode coinciding in frequency in both loops. This condition dictates that one of the fiber lengths is shorter than the other, so the resultant Q of the combined loops is lower than the Q of the longest length of fiber. A modified version of multi-loop configuration to reduce or eliminate the unwanted noise peaks while providing the best performance and lowest degradation of high Q of the long fiber was assembled as a pair of coupled OEO injection locked to each other [11]. This scheme was recently modified to optimize the performance by careful control of phase and amplitude of mutually injected signals of the OEO pair [21].

It is desirable to reduce the unwanted supermodes by decreasing the length of the fiber to increase the frequency of the modes so that they might lie outside the filter bandwidth. This, however, reduces the high Q associated with the length of the fiber delay. A way around the problem is the COEO scheme. In the COEO, the active optical loop essentially functions as a Q multiplier of the oscillator. So a shorter fiber length in the COEO can produce a lower phase noise than with the same length of fiber in the OEO, while at the same time practically eliminating the unwanted supermodes. This scheme also has the desirable feature of a more compact size associated with the short length of fiber, with the added benefit of lower sensitivity to environmental perturbations [10].

With advances in technology of optical modulators and detectors, the operating frequency of the OEO is also on the rise. Early on, operation at 39 GHz was demonstrated [12], but recently an OEO operating at 50 GHz has also been produced [13]. As the frequency of operation increases, effect of laser noise and dispersion on the phase noise produced by the oscillator must be taken into account [14].

B. OEO Based on WGM Resonators

A new direction in OEO technology is the application of WGM resonators, both, as the filter and the high Q element. The basic configuration is depicted in Figure 2. Because a semiconductor laser can be locked to the high Q resonator, as well, this scheme has the added benefit of small size and low operation power. These are important benefits for applications where size and power are important. There are two basic approaches for realization of the WGM resonator-based OEO: direct modulation of the laser current or external modulation using a resonator made with electro-optic material. In the former case, the resonator can be fabricated with crystalline material, such as calcium fluoride or magnesium fluoride, to achieve extremely high Qs.

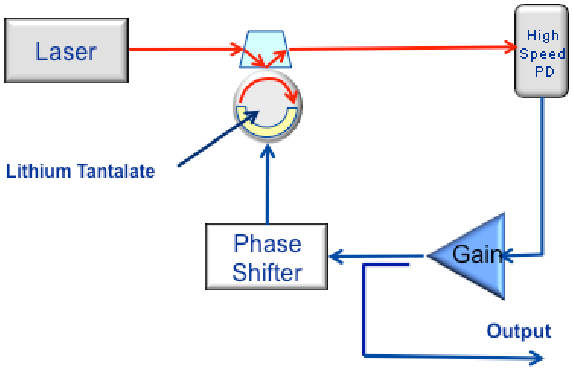

Figure 2 Schematic diagram of the OEO based on a lithium niobate modulator made with a whispering gallery mode resonator

Optical resonators with Q exceeding 10^{11} have been demonstrated with these materials [15]. The noise corresponding to this high Q is quite low, but the frequency of the oscillator is limited to the bandwidth of the modulation frequency of the laser, and is typically limited to x-band frequencies. Given the growing interest in higher frequency oscillators, the WGM resonator serving as a modulator can be more attractive. Here, the resonator is fabricated with electro-optic material, such as lithium niobate or lithium tantalate, and provided with electrodes that can be used to apply the modulation voltage. The narrow resonance of the resonator serves to provide low phase noise in the oscillator circuit; it also leads to highly efficient modulation and thus reduction for needed amplification. It should be mentioned that an OEO with a WGM resonator as filter and an external phase modulator has also been demonstrated.

The latest advance in the technology of WGM based OEO is the use of a both TE and TM modes of the resonator. A modulator transferring photons from a single TE mode to TM modes has been shown to perform as a true single sideband (SSB) modulator. The SSB modulator is fundamentally more efficient, and thus can improve the performance of the oscillator. Furthermore, since the indices of refraction of the modes respond differently to a forcing function, such as temperature change or an applied voltage, the modulation frequency can be tuned. This approach has been recently implemented, and a tunable oscillator with a WGM resonator was demonstrated [16].

An different approach for generation of microwave and mm-wave signals takes advantage of the fact that a frequency comb generated with a femtosecond mode locked laser is essentially equivalent to a large number of narrow linewidth lasers that are separated in frequency by a fixed amount, and are all coherent with respect to each other. Such a comb can generate a signal at the output of a fast photodetector as a result of the beat generated by its tines. Because of the coherence of the very narrow comb lines, the signal produced has outstanding spectral purity, and can be combined with a stable optical reference to also provide high stability [19]. Recent work in this area has shown stand alone femtosecond combs with very high stability producing unmatched spectral purity at 1 and 10 GHz [18].

One of the shortfalls of the technique with femtosecond combs is that they are large, requiring a pump laser, and are generally limited to application in the laboratory environment. They also produce signals at frequencies around 10 GHz and lower. A recent advance in the generation of optical frequency comb using a WGM resonator has opened the door for generation of high spectral purity signals at virtually any desired microwave or mm-wave (and even THz) frequency. This is based on Kerr nonlinearity in the resonator material, which through the process of four-wave mixing and hyper-parametric oscillation allows excitation of many modes when one mode of the resonator is pumped with laser light. Moderate laser powers combined with the high Q of the resonator make this process possible [19]. Using the Kerr frequency comb, high spectrally pure mm-wave signals have been produced at about 35 GHz [20]. A clear advantage of this scheme is the small size of the Kerr comb oscillator that can support a wide variety of applications in science and engineering [25].

Advances made with the comb oscillator appear to make the need for the OEO configuration less important. In fact, it can be shown that combining the OEO feedback loop with the comb will result in a regenerative architecture, similar to COEO. The outcome will be higher performance, by perhaps tens of dB, beyond what is achievable with the Kerr comb oscillator. This area represents a new focus for OEO research in the future, and will likely provide new results within the next few years.

In summary, the OEO architecture for generation of spectrally pure microwave and mm-wave signals has advanced considerably in the past few years. New schemes for realization of the OEO and use of optical combs promise to serve emerging applications to meet the ever stringent performance requirement of emerging applications.

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