

Recent Progress in Opto-Electronic Oscillator

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The optoelectronic oscillator (OEO) is a unique device based on photonics techniques to generate highly spectrally pure microwave signals [1]. The development of the OEO was motivated by the need for high performance oscillators in the frequency range larger than 10 GHz, where conventional electronic oscillators have a number of limitations. These limitations typically stem from the product of fQ , where f is the oscillator frequency and Q is the quality factor of the resonator in the oscillator. In conventional resonators, whether electromagnetic or piezoelectric, this product is usually a constant. Thus, as the oscillator frequency is pushed higher, the quality factor degrades, resulting in degradation of the phase noise of the oscillator. An approach to mitigate the problem is to start with a very high quality signal in the 5 to 100 MHz range generated by a quartz oscillator and multiply the frequency to achieve the desired microwave signal. Here again, frequency multiplication also results in an increase of the phase noise by a factor of $20\log N$, where N is the multiplication factor.

The lowest noise microwave oscillators based entirely on electronic approaches relied on extreme high Q of dielectric resonators made of sapphire. The penalty paid for this approach is cost, size, power consumption, and acceleration and temperature sensitivity.

Of course not all applications demand the highest spectral purity; many communications and test and measurement applications utilize lower spectral purity, but have cost and size constraints. Nevertheless, lower oscillator noise can enhance communications through increased channel capacity, and increase the performance of test and measurement systems.

The OEO is based on a photonics architecture, where light energy is converted to spectrally pure signals via an optoelectronic feedback loop [2,3]. In its most generic configuration the OEO consists of a light source, a device to modulate the light carrier's amplitude or phase, an energy storage device, and a fast photodetector that serves to convert the light into an electrical signal. This signal is amplified and filtered and fed back to the modulator in a loop with gain equal to or larger than its loss. An electronic phase shifter ensures that the phase of the waves propagating in the loop add coherently, thus producing a self-sustained oscillator at a frequency determined by the filter center frequency. This architecture can most readily be demonstrated with a fiber delay line as the energy storage element. With this configuration, the fiber delay serves as the high Q , wide bandwidth element that can support any sideband frequency generated by the modulator. If the fiber has enough dispersion, a

phase modulator can be used to obtain an amplitude modulation at the photodetector; otherwise an amplitude modulator, such as a lithium niobate or electroabsorption based device, can be used.

The generic OEO architecture described above can yield very high spectral purity: a device capable of producing a spectral density of phase noise at -163 dBc, 10 KHz away from a 10 GHz carrier, has recently been demonstrated. But the versatility of the OEO architecture provides for other configurations that serve many other applications. For example, the use of the fiber delay produces peaks in the noise spectrum that correspond to the frequency associated with the length of the loop. Since waves that circulate the loop can add coherently, the fiber based OEO is essentially a multi-mode oscillator that is forced to oscillate at a single mode determined by the center frequency of the filter. But the filter has a finite bandwidth and any other mode with frequency that falls within the bandwidth also survives, though at a much reduced power level. These modes appear as noise sidebands in the spectrum of the oscillator. One approach to reduce the influence of the noise sidebands is to use two or more fiber loops with different lengths to serve as a filter [4]. Another approach is to use a high Q optical resonator with wide free spectral range (FSR) to eliminate any modes other than the selected one. The use of optical whispering gallery mode (WGM) resonators allows realization of such architecture in a size that is significantly smaller than the fiber based device.

The fiber based OEO, on the other hand,

can also be realized in a coupled optoelectronic oscillator (COEO) [5] with a shorter length of fiber, which increases the corresponding FSR. In this way noise sidebands are pushed out to higher frequencies, where their effect is less objectionable, and the amplitudes are further reduced by the filter. The presence of these modes, nevertheless, can be used to advantage in a configuration where a tunable filter selects a mode that corresponds to a desired frequency, realizing a high performance tunable oscillator.

Many features of the OEO mentioned above have been demonstrated in the past ten years. Recently, however, considerable progress has been made in extending various features of the OEO to regimes that are particularly interesting for a number of new applications. In the remainder of this paper an outline of recent progress will be introduced.

Fiber based COEO:

In the generic OEO, a laser external to the optoelectronic feedback loop provides the optical energy. The COEO is a configuration where the source of the optical energy is placed within the feedback loop [5]. This is accomplished by using an optical amplifier, such as an erbium doped fiber amplifier (EDFA) or a semiconductor optical amplifier (SOA), whose output is used as its input. The amplifier then naturally oscillates to produce a laser that if left alone, will operate in a multimode regime with considerable instability. This laser, however, can be used as the source of light within the COEO's electrical feedback loop, using the modulator to link the two loops. The light generated by the optical loop

produces the microwave signals in the electrical loop, which is fed back to the modulator to mode lock the optical source as well.

The COEO will operate with low noise if the OEO segment of the loop has a long fiber delay for high Q [5]. Under the right conditions, though, low noise can also be obtained with a short fiber in the optical loop of the COEO. It can be shown that in this configuration the optical source serves as the Q element of the microwave oscillator loop [6]. But the optical source is an "active Q" element, since the gain in the optical loop is high enough to support lasing. The value of this active Q is determined by the parameters of the laser, including the gain bandwidth of the optical amplifier, and the bandwidth of the optical filter. An oscillator based on this configuration was demonstrated with an EDFA and less than 400 m of fiber in the optical loop. The "active Q" generated by this loop for the electronic microwave oscillator was equivalent to more than 10 km of fiber. Yet, because of the short length, the FSR of the oscillator was large enough that the corresponding noise side modes were at higher frequency and below -140 dBc level. This oscillator also demonstrated another important feature of the OEO/COEO: the noise performance of this photonic oscillator at frequencies close to the carrier is limited by the flicker noise of the electronic amplifier. A particularly low noise amplifier yielded a phase less than -150 dBc at 10 kHz from the carrier with the COEO described above.

The Tunable Oscillator:

A major feature of the OEO/COEO architecture is tenability. As mentioned above, without a discriminating filter many modes simultaneously oscillate in the loop, separated in frequency by the FSR corresponding to the fiber delay. Using a tunable filter, any of the modes can be selected resulting in a single mode oscillator at the frequency set by the filter. There are two important differences between this photonic tunable oscillator and the electronic tunable oscillator. In the case of the photonic loop, all modes essentially exhibit the same phase noise, since the Q element is optical and wideband. Thus within the tuning bandwidth of any filter that operates in the GHz regime, all losses within the loop are the same for all modes, and thus there is no penalty paid in increasing the frequency of oscillation. The second important difference is that the high Q of the oscillator is due to the photonic storage element, rather than the filter. Thus unlike the electronic oscillators, there is less sensitivity to the variation of the voltage or current that tunes the filter. Finally, the filter in such an oscillator can be a wideband electrical filter, or a photonic microwave filter based on WGM resonators.

A tunable oscillator with a wideband YIG filter was recently demonstrated [7]. This oscillator can be tuned across the tuning bandwidth of the filter, which covers the band from 2 to 12 GHz. The noise of this widely tunable oscillator at 10 kHz from the carrier is -140 dBc, and is equal to the phase noise of a fixed 10 GHz oscillator made with the same components, and a fixed filter. This performance is simply limited by the flicker noise of the amplifier.

Miniaturization of the Oscillator:

The optical components in the OEO/COEO can in principle be based on semiconductor devices, and thus be extremely small in size. This is not true, however, for the fiber coil that serves as the high Q element of the oscillator. A scheme must be devised to produce high optical Q's in a small volume. An approach based on the use of whispering gallery mode optical microresonators addresses this challenge. WGM resonators are centro-symmetric open dielectric resonators with electromagnetic modes that support wave propagation close to the surface of the resonator [8]. A feature of these modes is a very high Q resulting from negligible scattering loss and bending loss, since the surface of the resonators is fabricated to be smooth, and the diameter of the resonator, typically from a few 10's of micron to a few mm, is much larger than the wavelength of light. The largest source of loss in these structures is material absorption that is extremely small in glass. Recently, fabrication of these structures with crystalline material has led to the realization of optical Q exceeding 10^{10} . This high Q can be utilized in lieu of the long fiber delay in the OEO/COEO configurations. Oscillators based on this scheme have been realized with the resonator serving as both the Q element, and the filter in the oscillator [9]. The latter feature is obtained since the resonator can only support modes separated by its FSR, which also determine the oscillation frequency. This approach has recently been combined with the SOI fabrication technology to produce a fully integrated OEO. Such a device will find myriad of applications in future photonics systems.

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