Progress in the Opto-Electronic Oscillator – A Ten Year Anniversary Review

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***Abstract* – The opto-electronic oscillator (OEO), which uses an optical energy storage element to achieve low phase noise, represents a paradigm shift for generating high quality microwave signals. Since its first demonstration of low phase noise potential ten years ago at JPL, the OEO has been steadily improving its phase noise performance, frequency stability, and robustness. Now the OEO has moved beyond the laboratory and entered into real world applications, ranging from aerospace to telecommunications to instrumentation.**

***Index Terms* – Low noise oscillator, sources, phase noise, microwave oscillator, micro-resonator, opto-electronic**

I. INTRODUCTION

The quality of the signal produced by any oscillator critically depends on the energy storage time in the oscillator circuit. High-Q or low-loss energy storage elements are essential for generating high spectral purity and high stability microwave signals. Before the invention of the opto-electronic oscillator (OEO), almost all high performance microwave oscillators were either built with microwave energy storage elements (such as dielectric resonators), or acoustic energy storage elements (such as quartz resonators). These elements have limited frequency range and are best suited for signals from megahertz (quartz resonators) to a few gigahertz range. The energy storage times of these types of elements degrade drastically at high frequencies beyond X-band, which makes generating low phase noise microwave signals at tens of gigahertz and beyond a challenge.

The OEO represents the first practical microwave oscillator that uses optical energy storage elements to achieve high spectral purity at frequencies ranging from about a hundred MHz to beyond 100 GHz. This feature opens a new paradigm for generating high quality microwave signals. A host of optical energy storage components– such as fiber Fabry-Perot resonators, fiber ring resonators, and optical micro-disk resonators can be used to construct an OEO, in addition to a long length of optical fiber reported in the first demonstration. The use of optical resonators can drastically reduce the size of the OEO. The optical micro-disk resonator is particularly important because it is the key element in realizing the integration of an OEO on a chip.

II. THE OEO ARCHITECTURE

The first OEO was demonstrated in 1994 [1] (Fig. 1) and it consisted of a laser source, an electro-optic modulator (EOM), a long fiber link, a photodetector, followed by an electrical amplifier and a filter, which closed the feedback loop on the modulator. In this configuration, oscillation starting with noise was amplified and filtered at the desired frequency before being fed back to the modulator. The fiber link served as the delay, providing the needed quality factor (Q) for low noise oscillation. Since all waves that propagate in the loop and add up in phase can sustain oscillation, the generically multi-mode OEO requires the filter to select the mode with the desired frequency, while suppressing the unwanted modes.

A major benefit of the OEO configured in this manner is that it can be readily analyzed to obtain closed form expressions for its operation and performance. We use a model by setting the small signal gain of the feedback loop consisting of the EOM, the photodetector, and the RF amplifier to unity. [2,3]

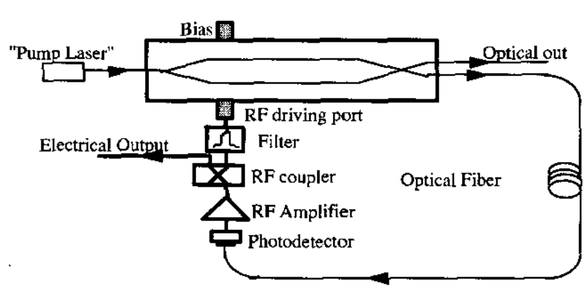

Fig. 1. Generic configuration of the OEO.

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Referring to Fig. 1, the signal $V_{out}(t)$ at the output port of the amplifier corresponding to an input signal $V_{in}(t)$ at the driving port of the E/O modulator can be expressed as:

$$V_{out}(t) = V_{ph}\{1 - \eta \sin \pi [V_{in}(t)/V_\pi + V_B/V_\pi]\} \qquad (1)$$

where $V_{ph} \equiv I_{ph} R G_A$ is the photon generated voltage at the output of the amplifier, V_B is its bias voltage, V_π is its half-wave voltage, and η determines the extinction ratio of the modulator by $(1+\eta)/(1-\eta)$. R is the load impedance of the detector, G_A is the amplifier's voltage gain, and $I_{ph} \equiv \alpha P_o \rho / 2$ is the detected photocurrent where α is the fractional insertion loss of the modulator, P_o is the input optical power, and ρ is the responsivity of the detector. Based on this model, we showed that the threshold condition for the oscillation may be obtained as:

$$V_{ph} = V_\pi / \pi \,, \qquad (2)$$

assuming $\eta = 1$ and $V_B = 0$ or V_π.

As a next step, Eq. 1 may be linearized through the use of a narrow bandwidth filter to block all harmonic components of the signal. The result of this procedure allows the application of the superposition principle and regenerative feedback approach to derive the spectral power density of the oscillation:

$$S_{RF}(f') = \frac{\delta}{(\delta/2\tau)^2 + (2\pi)^2(\tau f')^2} \quad \text{for} \quad 2\pi f' \tau << 1 \qquad (3)$$

where f' is the frequency offset from the oscillation frequency and δ is the noise to signal ratio of the OEO and is defined as:

$$\delta \equiv \rho_N G_A^2/P_{osc} = [4k_B T(NF) + 2eI_{ph}R + N_{RIN} I_{ph}^2 R] G_A^2/P_{osc} \,, \qquad (4)$$

where ρ_N is the total noise density input to the oscillator and is the sum of the thermal noise $\rho_{thermal} = 4k_B T(NF)$, the shot noise $\rho_{shot} = 2eI_{ph}R$, and the laser's relative intensity noise (RIN) $\rho_{RIN} = N_{RIN} I_{ph}^2 R$ densities. In Eq. (4), k_B is the Boltzman constant, T is the ambient temperature, NF is the noise factor of the RF amplifier, e is the electron charge, I_{ph} is the photocurrent across the load resistor of the photodetector, and N_{RIN} is the RIN noise of the pump laser. Note that Eq. 3 does not contain the oscillation frequency. This is the basis for an important feature of the OEO: the noise of an OEO is fixed, and will be the same at any frequency, as selected by the filter. Thus the OEO does not have the noise multiplication penalty as it is operating at, say, 5 GHZ or 50 GHz, as selected by the filter. This statement, of course, assumes that the noise of the amplifier is the same at 5 GHz and 50 GHz.

It is clear from Eq. 3 that the noise of the oscillator is influenced by length of the fiber delay (proportional to τ). So evidently the noise can be reduced by any desired amount by simply lengthening the fiber. While true, this notion provides practical challenges. As the fiber length increases, the number of modes increases, and the frequency between the modes (free spectral range or FSR) becomes smaller. This implies that a very narrow-band filter is required in order to eliminate the unwanted modes. High-Q filters in the microwave domain are difficult to realize, and so an OEO with a long fiber delay generates unwanted modes. One approach to overcome this difficulty is to use a filter in the optical domain, consisting of two (or more) loops of fiber with short and long lengths. [4-6] Since an oscillator with this architecture will have to satisfy the mode structure of both fiber lengths, then the FSR of the short fiber serves to eliminate or reduce the influence of the modes in the longer fiber, which provides the high Q. Such a configuration with three loops of fiber was recently developed at OEwaves, and is depicted in Fig. 2A. [6,7] An early OEO based on a dual loop configuration has achieved an impressive low phase noise of −140 dBc/Hz at 10kHz away from a 10GHz carrier. [4,6] This is also shown in Fig. 2B as measured recently at OEwaves.

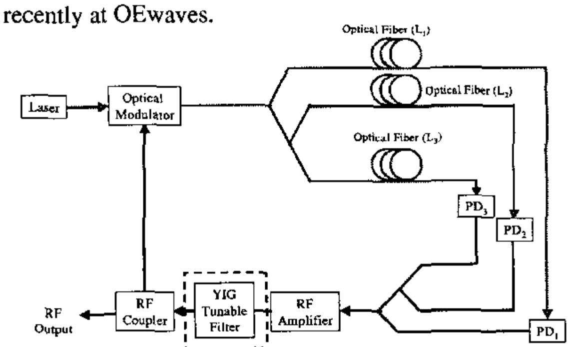

Fig. 2A. A triple optical loop OEO configuration, with YIG tunable filter for tunable OEO configuration.

The presence of many modes in the oscillator, nevertheless, can be put to advantage. Since the oscillator can operate at any mode frequency, placing a tunable filter in the loop produces a tunable OEO that generates signals centered at the selected mode frequency, and continuously tunable (with a phase shifter) within the FSR. A notable feature of the tunable oscillator is that all signals display the same high spectral purity, without degradation as the frequency is increased. An oscillator based on this concept was developed at OEwaves in 2002 [6,7] and is depicted in Fig. 2A.

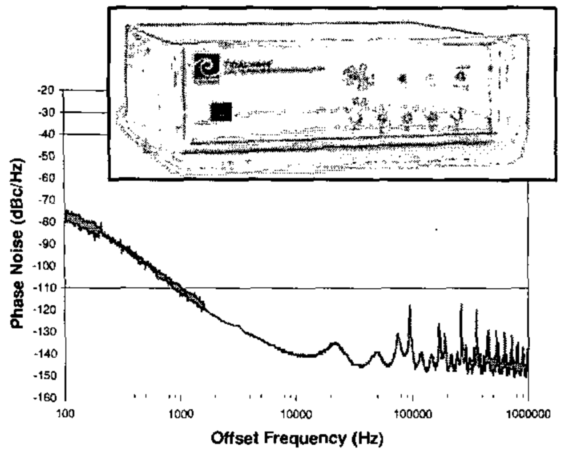

Fig. 2B. Phase noise of dual loop OEO [6]; inset is a photograph of the commercial device.

These early realizations of the OEO architecture were followed by approaches that put the photonics aspects of the oscillator into further advantage. In particular, it is clear from Fig. 1 that the operation of the OEO is based on an optical source of energy, any modulation scheme, any optical energy storage (Q) scheme, followed by a photomixer. So the source of the light energy, for example, could be an optical amplifier that has its output feedback to itself to generate an optical oscillator. This allows placing the source of light *inside* the OEO loop, as depicted in Fig. 3. This Coupled Opto-Electronic Oscillator (COEO), first demonstrated in 1997 [8,9], generates short optical pulses at its optical output, and highly spectrally pure signals at its electrical output. The optical pulses are at the frequency of the microwave oscillation which is selected by the microwave filter.

An advantage of the COEO architecture is that it can be combined with an optical storage element, such as a cavity. In particular the use of whispering gallery mode (WGM) optical micro-cavities allows miniaturization of the OEO by eliminating the bulky fiber delay. [10,11] Another advantage of this scheme is that the large FSR of the WGM cavities (set the desired oscillation frequency) essentially eliminates the unwanted modes of the OEO.

A micro-disk resonator operating in whispering-gallery modes can be used, as shown in Fig. 4. The micro-disks are generally made with fused silica, the same low loss material used in optical fibers. Light coupled into a micro-disk undergoes total internal reflection at the boundary between the fused silica and the air in a similar fashion as light propagating in an optical fiber. It goes around and around along the equator of the sphere so that the effective optical path length is dramatically increased, just like in a fiber ring resonator. It is predicted that the effective path length of a micro-disk of a few hundred microns in diameter operating at 1550 nm can be as long as 10 km, limited by the intrinsic attenuation of the material.

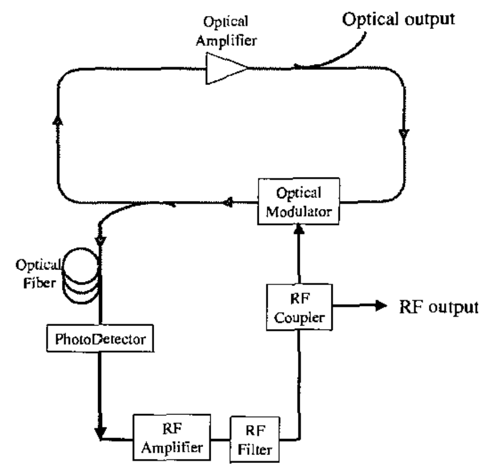

Fig. 3. The coupled opto-electronic oscillator (COEO) configuration.

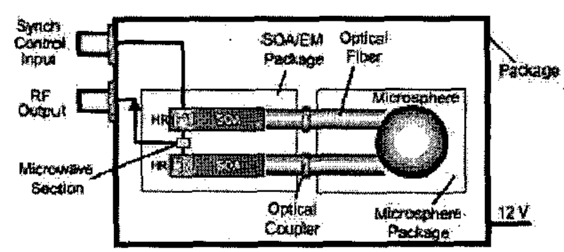

Fig. 4. OEO configuration with a micro-resonator replacing the optical fiber spool.

Recently, we proposed an active mode locked laser based on whispering-gallery modes in Er:LiNbO3 resonator. [12] This configuration, with a regenerative microwave feedback, can be used to fabricate a tiny multi-GHz oscillator, where the active medium that generates the light and the resonator are combined together in the same media. This microwave oscillator will consume very low power, will be compact and non-expensive, opening totally new possibilities and applications for the OEO.

III. Applications

The breakthrough concept of the OEO in its various configurations enables a wide range of military and commercial communications applications. The fiber based OEO in a rack-mount chassis serves as a clean microwave reference signal source for bench-top laboratory or manufacturing test applications while the miniaturized micro-resonator based OEOs are suitable for a variety of radars (including phased array), electronic warfare (EW), signal intelligence (SIGINT), satellite communication, digital microwave radio, broadband wireless, high frequency signal processing, and microwave test equipment applications, among others. As a unique optical signal source, the COEO is an ideal return to zero (RZ) pulsed optical source and a multi-wavelength optical source for dense wavelength division multiplexing (DWDM) optical transmission applications.

IV. Conclusion

A miniature OEO based on the technology outlined above is being developed at OEwaves, with the first prototype available in early 2004. This device represents the extension of the original OEO architecture to a compact, high performance device that will enable a large number of applications ranging from high performance radar to communications devices. In the future, the scheme for the miniature OEO will be extended to tunable units and a single chip architecture, allowing significant cost reductions for applications in future hand held devices operating in high data rate modes. At the tender age of 10, the OEO architecture is still in its youth, as compared to other oscillator technologies such as quartz and microwave oscillators. This novel scheme promises to enable new capabilities, allowing novel systems architectures that can benefit from its unique performance features: High spectral purity, high operating frequency, and small size, power consumption, and cost.

Acknowledgements

The authors would like to acknowledge and thank all members of the OEwaves and JPL teams that have contributed to the advancement of the OEO over the last 10 years.

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