A New class of opto-electronic oscillators (OEO) for microwave signal generation and processing

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ABSTRACT

A new class of oscillators based on photonic devices is presented. These opto-electronic oscillators (OEO's) generate microwave oscillation by converting continuous energy from a light source using a feedback circuit which includes a delay element, an electro-optic switch, and a photodetector. Different configurations of OEO's are presented, each of which may be applied to a particular application requiring ultra-high performance, or low cost and small size.

1. INTRODUCTION

Oscillators are ubiquitous in a variety of scientific, technological, and commercial applications. in communication systems, all receivers and transmitters process signals generated by, or compared to, reference frequencies produced by reference oscillators.

in conventional oscillators of communication systems, electrically generated frequencies are used in conjunction with high Q resonators to produce reference signals with high spectral purity and/or stability. Since the Q of these types of resonators typically degrade with increased frequency, reference signals at frequency of a few to tens of GHz are obtained by multiplying the lower frequency of the reference oscillator, at a cost of generating multiplicative noise. For optical and photonic communication systems, in yet an additional step, the electrical signals are impinged on an optical carrier, further aggravating the noise and the complexity of the systems.

Recently we introduced a novel oscillator based on photonic components which directly generates spectrally pure and stable references at 1-100 GHz region of the spectrum as intensity modulations of an optical carrier.[1] The first versions of this type of oscillator demonstrated unprecedented spectral purity in a room temperature device and a potential for high stability.[2,3] Since that time, we have devised various techniques to operate these oscillators without electrical amplifiers or filters. in this paper we will review the basis of the operation of these oscillators, and subsequently show that they comprise, a subclass of a more general type of Opto-Electronic Oscillators (OEO's) with various performance characteristics to suite the application of interest.

2. REVIEW OF THE CHARACTERISTICS OF THE OEO

The OEO is a device that converts continuous energy from a light source to stable, and spectrally pure oscillations. The first version of the OEO consisted of a pump laser and a feedback circuit including an intensity modulator, an optical fiber delay line, a photodetector, an amplifier, and a filter, as shown in Fig. 1.

This oscillator represented a particular version of the OEO, which in general can be made from any light source together with any device that can be configured in a closed loop to modulate the intensity or phase of the optical carrier. The fiber delay line which plays the role of the conventional high Q resonator for storing energy determines the spectral quality of the signal produced. The version shown in Fig. 1, however, is readily amenable to analysis to derive the expected performance of the oscillator theoretically.

Wc have used a model[3] by setting the small signal gain of the feedback loop consisting of the E/O modulator, the photodetector, and the RF amplifier to unity.

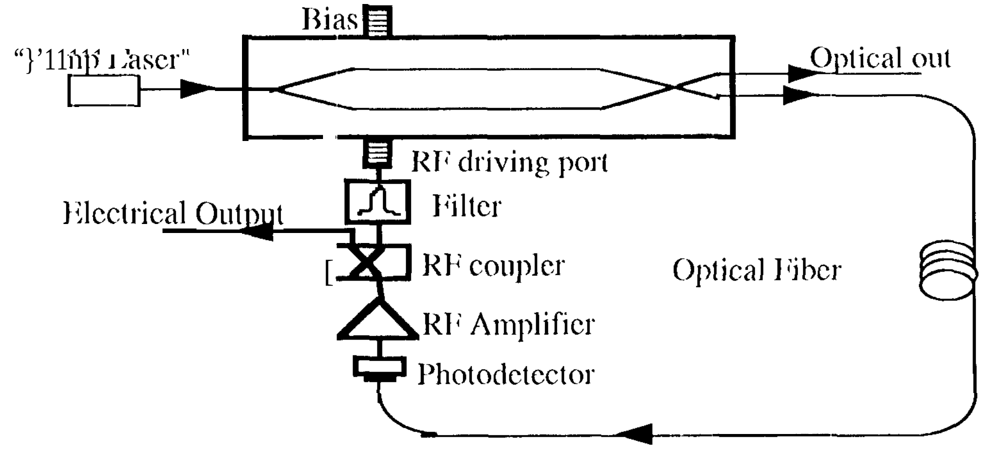

Fig. 1 Generic configuration of the OEO.

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

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

where f' is the frequency offset from the oscillation frequency f_{osc} 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.

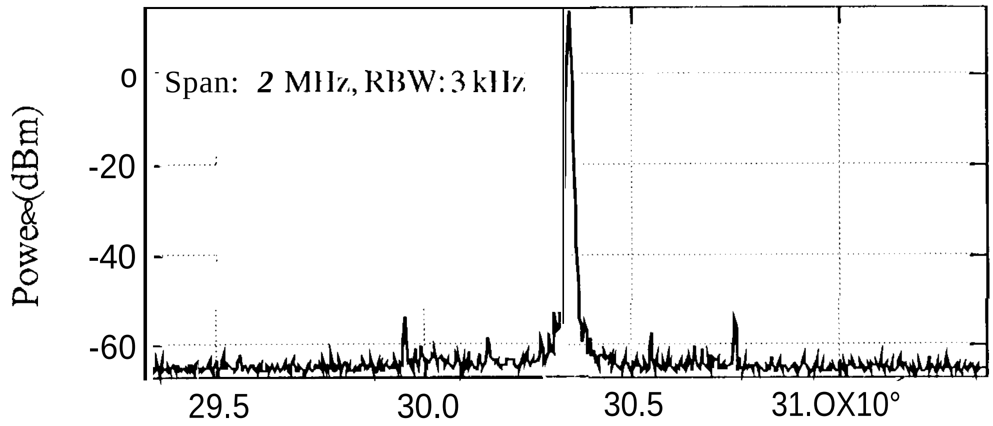

Fig. 2. OEO spectrum without an amplifier.

It is clear from Eq. 3 that the noise of the oscillator is influenced by the amplifier noise. Yet the requirement for self-sustained oscillation given by Eq. 2 implies that to sustain oscillations in the loop (i.e. $G_A = 1$) only the condition $I_{ph} R \geq V_\pi / \pi$ has to be satisfied. Thus it is possible to obtain oscillations with the OEO without an rf amplifier and its associated noise. This prediction is verified experimentally with an oscillator operating without an amplifier. Figure 2 represents the spectrum of the signal of such an OEO with a 1 km delay at a frequency o-f about 30 Mhz.

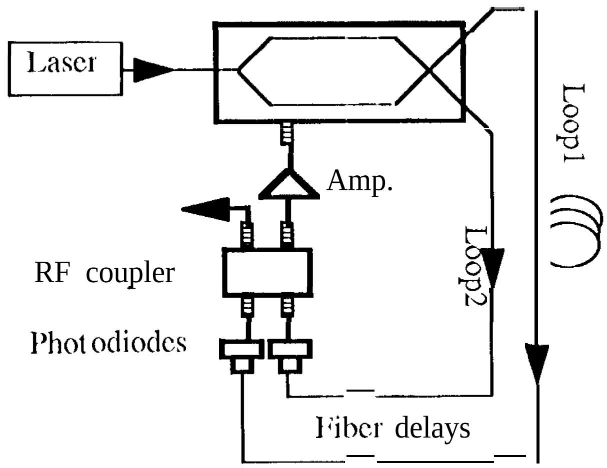

Fig. 3. The Dual Loop OEO

With the elimination of the amplifier, all other components, except for the filter, are photonic. The filter' is required to obtain a single mode operation Of the OEO which is inherently a multi-mode device. The long delay produced by the fiber to improve the noise performance as prescribed by Eq. 3 above produces close mode spacing and thus necessitate the use of a narrowband rf filter.

We have recently demonstrated the operation of the OEO with a wide bandwidth rf filter. This was achieved by utilizing a short optical delay line (fiber) in a second feedback loop, as shown in Fig. 3.

in this configuration, the open loop gain of each of the two loops is individually less than unity, but their sum is larger than one. "The OEO's oscillation frequency is determined by both loops since the frequencies in each loop must add up in phase for self sustained oscillations. It can be easily shown that the shorter loop determines the mode spacing, which because of the small delay, is large, while the longer loop results in low phase noise. Thus a wideband rf filter suffices to produce low noise oscillations in this dual loop OEO.

3. OEO CONFIGURATIONS

It was mentioned above that oscillators serve a wide variety of applications, and thus assume many varied configurations to best suite the application of interest. The specific OEO configuration described above was designed to meet the stringent requirements of ultra-high spectral purity and stability. The use of a solid state laser as a light source ensures that the laser RIN, which sets the ultimate limitation of the oscillator noise, is minimized. Once the solid state laser is selected as the light source, an external modulator provides the "valve" to switch the laser intensity on and off. The external modulator also enables higher frequency operations, up to the limit of present day E/O modulators which is about 90 GHz. A long fiber delay ensures minimized noise, as well, and the elimination of the rf amplifier results in the elimination of yet another noise source, namely the amplifier flicker. Thus the configuration above is suitable for stringent applications such as radar and radio science, as well as frequency metrology.

in many other applications lower spectral purity and stability may be tolerated as trade off for size and cost. Examples of such applications include digital networks and personal communication devices. The principle basis of the OEO, namely the conversion of the continuous light energy to stable microwave oscillations, may be utilized to design other configurations to serve such applications. These new configurations may utilize any light source, such as semiconductor lasers or LED's, and short optical delays to afford integration in small packages.

A configuration utilizing a semiconductor laser and feedback to directly modulate its current is shown in Fig. 4. This oscillator has been reported previously[4], and recently demonstrated by us, and by a group at NIST.[5]

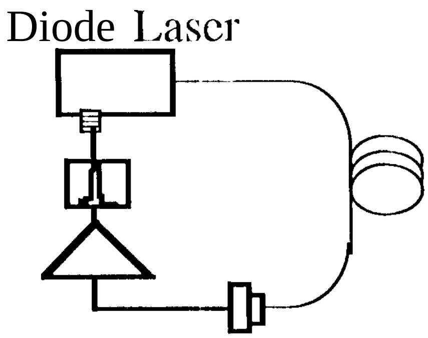

Fig. 4. OEO with a directly modulated DFB laser

The advantage of the semiconductor laser is its small size, and the elimination of the external modulator to achieve a small package. This feature is traded off for the relatively higher RIN of the semiconductor laser. An LED may also be substituted for the laser in applications where higher noise may be tolerated.

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If the oscillation frequency of interest is in the M Hz or smaller regime, a higher sat uration power, lower speed detector may be used to eliminate the rf amplifier in this configurat ion as wc]].

Other configurations utilizing a polarization switch in place of the E/O modulator also may be constructed. Here the feedback of the detected optical power by the photodetector to the properly biased polarization switch serves to turn the light intensity on and off and sustain oscillations. In all such applications the delay in the feedback loop and the choice of an appropriate filter determines the oscillation frequency. Since polarization switches arc rather slow, an OEO of this configuration is suitable for lower frequency operation.

As yet another configuration, consider the usc of an optical semiconductor amplifier (OSA). Such an amplifier in the feedback loop in place of the modulator and initially biased just below threshold, will cause the loop to break down and oscillate. in this configurate ion the design has to take the saturation power of the detector into consideration.

The OEO of Fig. 1 employs an E/O $LiNbO^3$ modulator of the Mach-Zehnder type. An electroabsorption modulator may replace tbc Mach-Zehnder interferometer, for an oscillator readil y suited for 01 EIC configuration.

As the last configuration example of the OEO, consider a feedback loop utilizing an 1 E/O frequency shifter in line with a fiber Bragg grating filter. This device will convert frequency shifts to intensity modulations at the photodetector, the output of which is fedback to the frequency shifter. Sustained oscillations will ensue with proper laser power, and appropriate choice of the bandwidth of the frequency shifter and the Bragg filter.

4. SUMMARY

In this paper wc have described a new class of oscillators based on photonic devices. This class, the 010, is based on the generation of microwave oscillation from continuous light energy. The OEO includes configurations suitable for ultra-high spectral purity and stability, as well as small and low cost versions. It can include rf amplifiers and filters, or operate without the need for these elements, depending on the desired applicat ion. Several OEO configurations were presented based on the usc of LED's, semiconductor lasers, and solid state lasers. Depending on the application of interest, onc of the light sources above may be combined with an electro-optic switch such as an intensity modulator, a polarization modulator, or a frequency modulator combined with a fiber Bragg grating. The switching frequency determines the operat ion frequency of the OEO. in other versions, the LED or the semiconductor laser may be directl y modulated. These configurations should make the OEO an ext remel y versat ilc and useful device for photonic and optical applications.

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5. REFERENCES

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