SOURCES

The optoelectronic oscillator

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Photonic technology can now be used to construct miniature sources of high-frequency radio waves that have exceptional spectral purity.

In the early 1980s, researchers at NASA's Jet Propulsion Laboratory in California realized that stable reference signals generated by a hydrogen maser atomic clock could be distributed over optical fibres to multiple antenna sites at NASA's Goldstone radio telescope facility in the Mojave Desert. The idea was to reduce the high cost of installing and maintaining hydrogen masers at each antenna site by instead delivering radiofrequency (RF) reference signals from a single site to multiple users located tens of kilometres apart. However, such a long separation distance could not be served by coaxial cables — the usual choice for transmitting RF signals — as the loss of the system would be too high for practical use. Scientists instead decided to encode the RF signals onto light using lasers, modulators and low-loss optical fibre, which were rapidly finding widespread applications in optical communications. The signal distribution system at the Goldstone complex also provided the first example of an operational RF photonics link, in which RF, microwave or millimetre-wavelength signals are carried as modulation data on an optical carrier.

Subsequent work in the field of RF photonics at the Jet Propulsion Laboratory focused on developing other capabilities that could take advantage of the unique properties of optical components. One area of research pursued the realization of a microwave oscillator based on RF photonics. Oscillators are devices that produce periodic waves whose amplitude, phase and frequency can be precisely controlled to produce signals that carry information. Oscillators are an essential element in any system that receives or transmits a signal, and are widely used in communications systems, radar, signal processing, sensors, metrology, radio astronomy and a myriad of other applications where an electromagnetic signal is generated, received or processed.

Demanding applications require oscillators of very high spectral purity — systems capable of generating a near-perfect sinusoidal signal. The spectral purity of an oscillator is governed by the loss in its feedback circuit. To achieve the ultrahigh spectral purity levels required by advanced metrology, communications, radar and data transmission systems, oscillators with high-quality-factor (*Q*-factor) resonators are used to minimize the dissipation of energy circulating in their feedback loop. Piezoelectric quartz resonators, thanks to their extremely high *Q*-factors in the frequency range of 10–100 MHz, are particularly suitable for use in RF systems. As the frequency of the output is increased, the *Q*-factor of the electronic resonator degrades and the spectral purity deteriorates. Thus, for microwave and millimetre-wavelength applications in the gigahertz region, the best signals are generated with a multiplied output from a high-performance quartz oscillator operating in the megahertz range. However, this frequency multiplication process also multiplies the oscillator noise, which means the performance of microwave and millimetre-wavelength oscillators based on frequency multiplication will always degrade with increasing frequency.

Researchers at the Jet Propulsion Laboratory then decided to focus on the development of an alternative solution: a new type of high-performance oscillator known as the optoelectronic oscillator (OEO; Fig. 1). The OEO is based on the use of optical waveguides and resonators, which exhibit significantly lower loss than their electronic counterparts. In a typical OEO, light from a laser is modulated and passed through a long length of optical fibre before reaching a photodetector. The output of the photodetector is amplified, filtered, adjusted for phase and then fed back to the modulator. This feedback loop can generate self-sustained oscillation if its overall gain is larger than the loss and the circulating waves can be combined in phase.

The OEO architecture is quite versatile and can be configured to customize performance in a variety of

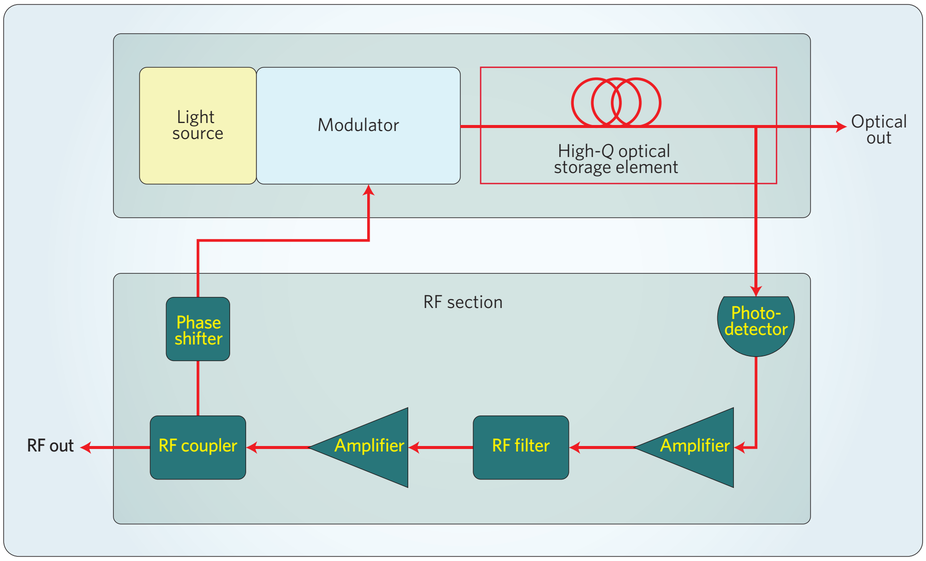


Figure 1 | Block diagram of a generic OEO.

ways using different optical and electrical components. The gain element, filter and phase shifter can be placed either in the optical segment or the electrical segment of the loop. The laser may be of any suitable type and wavelength, and the RF modulation can be achieved directly, for example by controlling the current applied to a semiconductor laser, or with an external modulator. Modulation of phase, amplitude or polarization can all be employed and the high-Q (low dissipation loss) optical cavity can be a Fabry–Pérot, whispering gallery mode resonator (WGMR) or long fibre delay with a Q-factor corresponding to its length. The operating frequency can be either fixed using a filter or tuned by changing the wavelength of the laser or the cavity's optical path length. Finally, the circulating light can be generated either by a laser external to the loop or in an optical loop whose optical gain can be coupled to the electrical loop through the modulator — a configuration known as the coupled optoelectronic oscillator. Researchers in a number of groups around the world have demonstrated OEO operation with such configurations at various radio, microwave and millimetre-wavelength frequencies.

The spectral purity of the signal in the OEO is directly related to the Q-factor of the loop. Most OEOs still utilize a long length of fibre to achieve high spectral purity. Indeed, the most spectrally pure 10 GHz oscillator demonstrated so far utilized a 16 km fibre loop. A disadvantage of using a fibre loop is the production of 'super modes' that appear in the phase noise spectrum. These modes — highly undesirable for certain applications — are caused by the propagation of waves multiple times around the OEO loop.

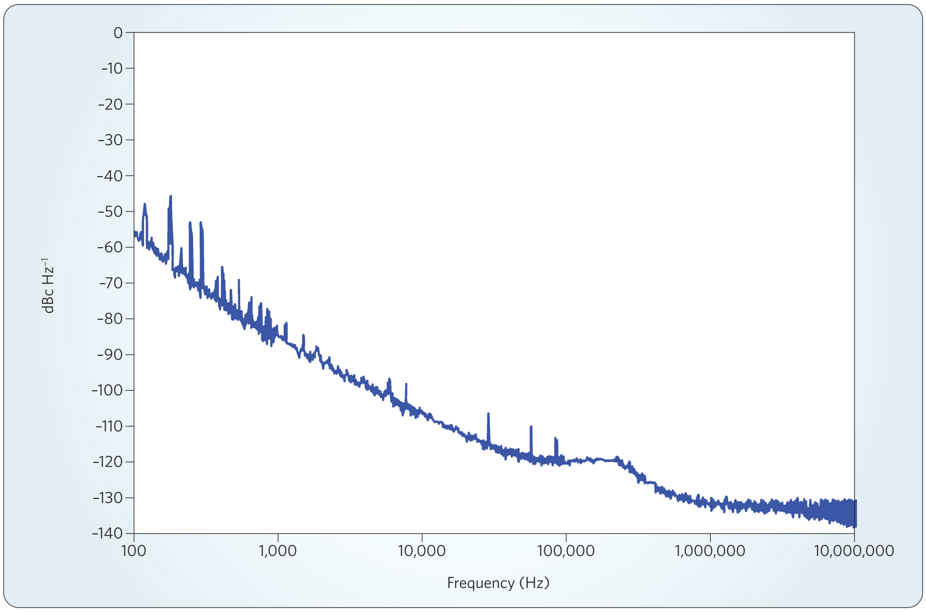


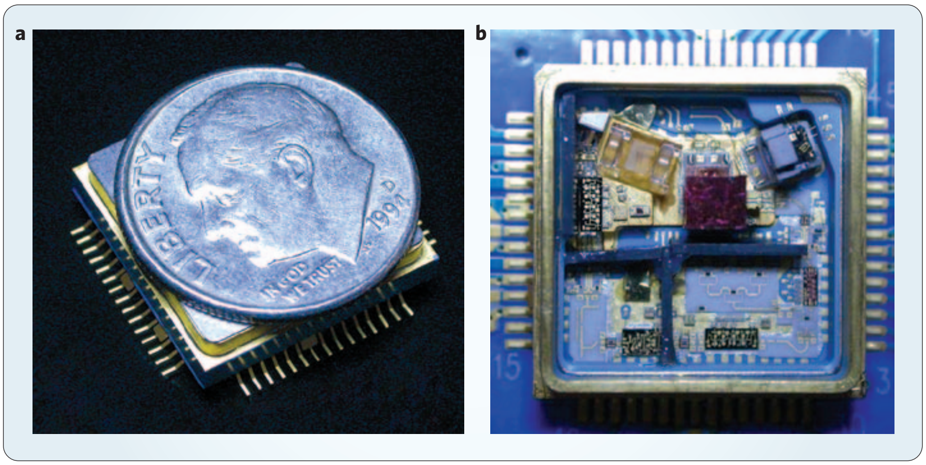
Figure 3 | Phase noise of a miniature 30 GHz OEO.

There are two effective photonic remedies for the removal or suppression of super modes. One scheme involves using multiple loops of fibre, which together essentially function as a narrowband filter. Another technique is to use a high-Q optical cavity to filter out the unwanted modes. Although Fabry–Pérot cavities with high Q-factors are useful for achieving this, a more convenient choice is ultrahigh-Q WGMRs.

WGMRs ranging in size from a few hundred micrometres to a few millimetres can be fabricated from a wide variety of optically transparent materials. In particular, WGMRs made from crystalline materials can have Q-factors in excess of a billion, with the largest reaching 3×10^{11}.

The bandwidths associated with such Q-factors are narrow enough to provide an effective remedy for removing unwanted super mode noise in the OEO spectrum.

Recently, a number of communications, data processing and radar applications have emerged that require high-performance microwave and millimetre-wavelength oscillators that not only are of miniature size but also have power consumptions many orders of magnitude lower than existing devices. This is a growing need, and optical oscillators based on WGMR technology are currently the only available solution. In particular, OEOs utilizing high-Q WGMRs made from an electro-optic material can provide high performance in a package smaller than a coin (Fig. 2). In this configuration, the resonator, excited with light from a semiconductor laser, serves both as the high-Q element and as the modulator in the OEO loop. The free spectral range of the resonator, which is related to its size, determines the frequency of the signal produced by this miniature OEO. This configuration can produce 30 GHz output signals with higher spectral purity than alternative high-power approaches. Oscillators based on this architecture are particularly desirable when high spectral purity is required in a small form factor at frequencies in the range of 10–40 GHz and higher (Fig. 3). These devices have already found applications in small military platforms and will soon enter commercial products such as broadband wireless communications systems.



OEWAVES

Figure 2 | Miniature OEO based on a lithium niobate WGMR.

US firm OEwaves recently introduced an oscillator design based on the use of Kerr optical frequency combs. Kerr frequency combs are generated by exciting a single mode of a miniature WGMR with light from a continuous-wave laser. Sidebands around the excited mode are generated when the intensity of the light is such that a four-wave mixing process can be excited in the resonator material. By increasing the applied optical power, a cascade effect produces a series of sidebands that form a frequency comb. The comb is essentially a series of phase-locked lasers separated in frequency by the resonator's free spectral range. It can be demodulated by a fast photodiode to produce a signal that is the product of the beating between the comb lines. Owing to the high degree of coherence and the large number of comb lines, the spectral purity of the beat frequency is extremely high.

Because optically transparent crystals such as calcium fluoride and magnesium fluoride can be used to produce ultrahigh-*Q* WGMRs, small semiconductor lasers emitting just a few milliwatts of power can excite nonlinear interactions and thus produce Kerr combs and associated RF signals. This architecture provides a simple, robust and efficient scheme for generating microwave and millimetre-wavelength signals in a tiny form factor.

An attraction of the resonator-based OEO architecture is that it is amenable to on-chip integration. An early programme run by the Defense Advanced Research Projects Agency (DARPA) in 2006 successfully combined an external resonator with a photonic chip fabricated on the silicon-on-insulator platform. The performance of the oscillators produced through this approach was limited by the noise performance of the electronic amplifiers fabricated by the CMOS process. Currently, a new DARPA programme aims to produce a 20 GHz oscillator with exceptionally high spectral purity based on an electronic–photonic heterogeneous integration process. Once demonstrated, such a chip-scale oscillator will be available with unmatched performance for applications across a wide variety of fields. ❐

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