Recent Developments in Optical Fibre Based Optoelectronic Oscillators

C. N. Ironside[1], Mohsin Haji[2], Anthony E. Kelly[2], Bruno Romeira[2], José M. L Figueiredo[2]
[1] Department of Imaging and Applied Physics, Curtin University, Perth, Western Australia 6845
[2] School of Engineering, University of Glasgow, Glasgow G12 8LT, UK
[3] Department of Physics, CEOT, University of Algarve, 8005-139 Faro, Portugal

Paper Summary
The paper reports recent progress on new types of low noise and high spectral purity optoelectronic oscillators operating at optical wavelengths around 1550nm and radio frequencies (RF) up to 40GHz with RF linewidths <1kHz.

Introduction
Optotoelectronic Oscillators (OEOs) are radio frequency (RF) oscillators that use a low-loss optical medium, usually optical fibres, for signal storage and phase memory, in combination with other optoelectronic components, this gives a low noise narrow linewidth oscillator. The first implementation of these RF photonic oscillators was reported in 1996 [1] and used optical fibre as the phase memory component of the oscillator.

In this paper we review recent advances made by our group in compact OEOs that have a reduced component count. We have produced OEOs at frequencies as high as 40GHz with linewidths as low as 192Hz. These OEOs not only have high frequency operation but by combining functions on a single optoelectronic chip have reduced complexity compared to previous OEOs.

OEOs can be used in applications that require low noise, stabile and compact RF oscillators for example frequency standards [2], radar systems [3] and in optical communication systems, for example, in optical clock recovery [4].

The Optoelectronic oscillator
In Figure 1 we illustrate the generic elements that make up an OEO.

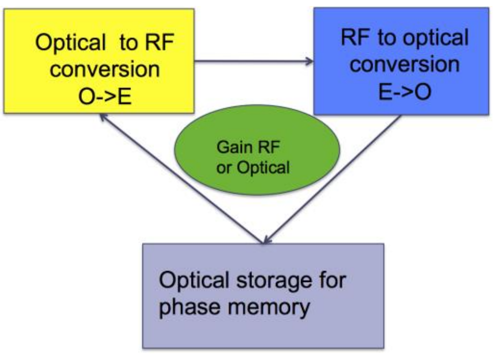

Fig. 1: Conceptual model that shows the generic elements that make up the OEO loop.

The key elements in the OEO loop are: optical to RF conversion, RF to optical and optical storage typically a length of optical fibre that provides low loss signal storage that gives the OEO a low noise and long phase memory. Also required to overcome any loss and obtain oscillation is some gain which can either be optical or electronic gain.

Here we present two approaches the modelocked laser diode (MLLD) OEO [5] and the resonant tunnelling diode (RTD) OEO [6]. In the MLLD-OEO system the MLLD combines optical to RF conversion, RF to optical conversion and some gain all in a single chip. In the RTD–OEO an RTD is combined with photodiode to provide optical to RF conversion and RF gain in the same component.

The Modelocked Laser Diode (MLLD) OEO
Semiconductor laser diodes can be passively modelocked by introducing a saturable absorber into the laser resonator – a convenient method for incorporating a saturable absorber is to have a multi-sectioned laser diode with electrically isolated sections. The forward biased section of the laser diode provides optical gain and the reversed biased section acts as a saturable absorber. When passively modelocked the laser produces ultrashort pulses (~1ps) at a repetition rate determined by the length of the resonator, L, - the repetition rate is given by, $f_r = c/2nL$, c- speed of light , n –refractive index. For typical laser diode dimensions, f_r, will be in the range 20- 100GHz and with harmonic modelocking this can as high as 2.2THz[7].

The stability of the pulse train emitted by the MLLD can be improved by providing feedback. In the OEO described here the feedback is arranged by taking the emission from the laser coupling into an optical fibre and looping the fibre back so its output is directed into the saturable absorber of the MLLD. The saturable absorber then neatly combines the two roles of optical to RF conversion and RF to optical conversion. The process can also be regarded as a self-synchronisation arrangement whereby the optical signal in the fibre is used as an injection signal into the MLLD and the MLLD locks onto a signal which is a delayed version of its output. The delay gives the OEO a phase memory.

The experimental arrangement is illustrated in figure 2. The MLLD is a multi-sectioned InP bas laser diode emitting at 1550nm [8]. The length of the laser diode gives a repetition rate, f_r, of 40 GHz. The loop also includes a Erbium Doped Fibre Amplifier that provides optical gain to overcome the losses in the feedback loop.

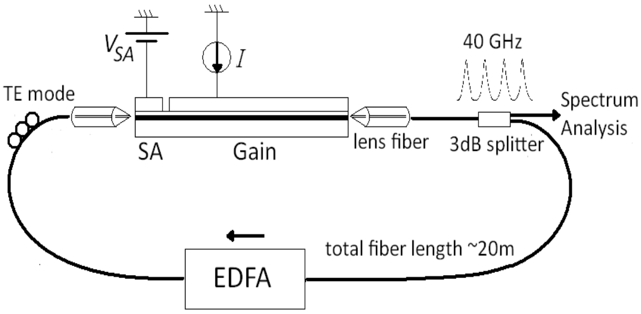

Fig. 2. A schematic of the Modelocked Laser Diode optoelectronic oscillator, SA, saturable absorber, EDFA Erbium Doped Fibre Amplifier. The length of the MLLD determines the repetition rate, 40GHz.

The results from MLLD-OEO illustrated in Figure 2 are shown in figure 3.

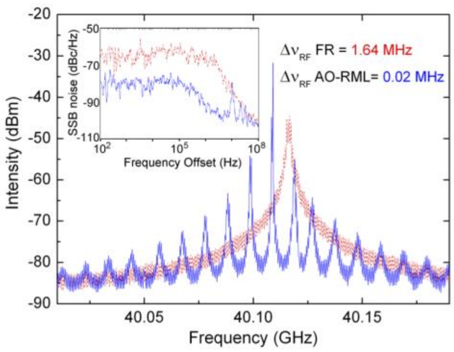

Fig. 3. The comparison spectra of the MLLD-OEO without fibre loop (Red) and with fibre loop (Blue) – the insert compares the single sideband noise.

From figure 3 it is clear that beside the main central there are spur peaks - from their spacing it can deduced that they are associated with the round trip of the fibre loop – these are so-called supermodes and they can be reduced by using two fibre loops as is illustrated in figure 4.

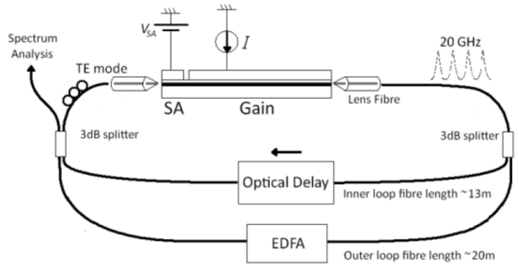

Fig. 4. The double loop MLLD-OEO compare with figure 3 – also note longer laser diode employed and therefore lower repetition rate (20GHz).

The double loop reduces the supermodes as can be seen in figure 5. The so-called Vernier effect introduced by the double loop suppresses the supermodes by a factor of 45dB. Under optimally stable conditions the 20GHz MLLD-OEO oscillates with a linewidth 192 Hz.

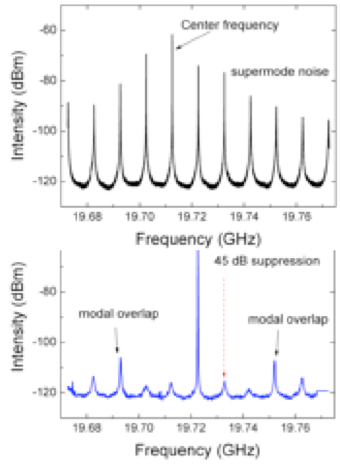

Fig. 5: Compares the spectrum of the MLLD-OEO with a single loop (Top figure) with the spectrum of the MLLD-OEO with a double loop (Lower figure) as in Fig. 4.

The resonant tunnelling diode OEO

The RTD-OEO employs a photodiode that includes a resonant tunnelling diode [6]. The RTD provides the photo diode with electronic gain sufficient to drive a laser diode. So the with the RTD-OEO the optical to rf conversion and electronic gain are combined in the RTD photodiode. In fact there is sufficient electronic gain from the RTD photodiode that it oscillates on just the electronic feedback present due parasitic capacitance and inductance in the RTD photodiode packaging. Like the MLLD-OEO the RTD-OEO relies on self-synchronisation from an injection signal stored in a length of optical fibre to obtain improved stability and narrow linewidth operation.

An RTD [6] consists of epitaxial layers of semiconductor alloys that form a nanostructure of high and low bandgap material – a low band gap epilayers is sandwiched between two high band gap barrier layers – typical dimensions are 2nm barrier layers and the quantum well middle layer is around 6nm, Fig. 6(a). The barrier layers are thin enough that electrons that have a wavelength resonant with the bound state in the quantum well can tunnel through the device. This gives the RTD a highly nonlinear current-voltage characteristic, Fig. 6(b), when correctly DC biased the nonlinear current–voltage behaviour combined with the high-speed quantum tunnelling effect gives the RTD high bandwidth electronic gain. The semiconductor alloys are grown on InP - some of the alloys absorb light at 1550nm and so the device acts as a photodiode integrated with a high gain, high bandwidth electronic amplifier.

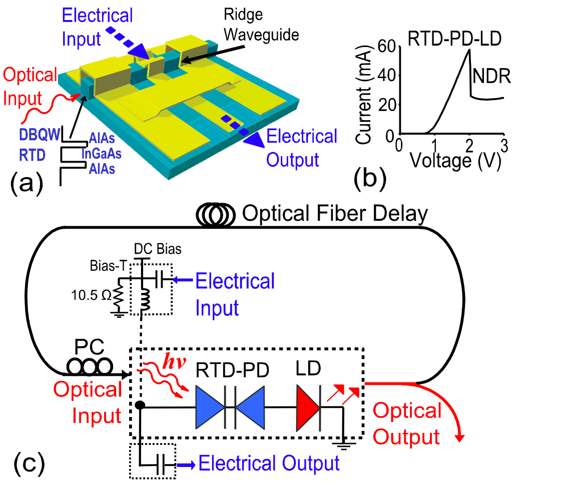

Fig. 6. (a) Shows the chip layout of the waveguide RTD photodiode (RTD-PD) (b) shows the current-voltage characteristic of the RTD-PD and laser diode combination (RTD-PD-LD), (c) shows the layout of the RTD-OEO and schematics of the electrical and optical output.

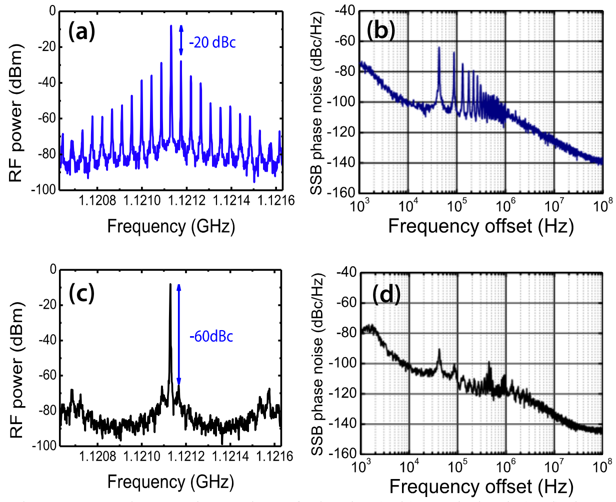

Fig.7. Experimental results of single (a,b) and dual (c,d) loop optical fiber RTD-OEO. (a) RF power spectrum and (b) SSB phase noise in a 4.4 km single loop configuration. (c) RF power spectrum and (c) SSB phase noise in a dual-loop arrangement.

Figure 6(c) illustrates some of the key features of the RTD-OEO. It consists of an RTD-PD driving a laser diode, and an optical fiber delay line in an optoelectronic feedback configuration. When compared with other OEOs, RTD-OEOs do not require separate RF or optical amplifiers, are more compact and with low power consumption, and have potential for fully monolithic integration.

Figure 7 presents the RTD-OEO experimental results employing both single and dual loop arrangements. In Fig. 7(a) is shown the RF power spectrum of a 4.4 km single loop RTD-OEO operating at ~1.211 GHz. Also shown are the side modes separated from the center carrier frequency by about 45 kHz, which corresponds to OEO supermodes with -20 dBc single-mode suppression ratio (SMSR). In order to verify the phase-noise reduction performance, single side band (SSB) phase noise measurements were performed. For an in-fiber optical power of ~9 dBm and an optical fiber length of 4.4 km, the corresponding phase noise value was -102.88 dBc/Hz, Fig. 7(b). A phase noise reduction of more than 40 dB at 10 kHz offset was achieved when compared to the free-running oscillations without light re-injection.

In a similar manner to the MLLD-OEO we employed a double loop optical fibre arrangement for the RTD-OEO. Figs. 7(c,d) present the results of an experiment employing a dual-loop RTD-OEO using a 4.4 km and a 0.4 km fiber loops. The longer fiber leads to high spectral purity and low phase noise at low offsets. The short fiber is able to suppress the side modes close to the carrier. In the case of the dual-loop configuration, the side mode suppression ratio was improved to about -60 dBc.

Conclusions

In this paper we have presented two approached to compact OEOs, the MLLD-OEO and the RTD-OEO. The share some common features, both have best performance using a double loop optical fibre arrangement, both employ self synchronisation and both combine OEO functions in a single chip. The RTD-OEO operates at lower frequency and has sufficient gain in the RTD photodiode so that it does not require an EDFA in the loop. The MLLD-OEO has operated at much higher RF frequencies and so far has operated up to 40 GHz which is amongst the highest frequencies reported for an OEO. Given that MLLD have operated with repetition rates up to 2.2 THz - the MLLD-OEO could bring the benefits of the OEO, narrow linewidth and low noise operation to THz oscillators.

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