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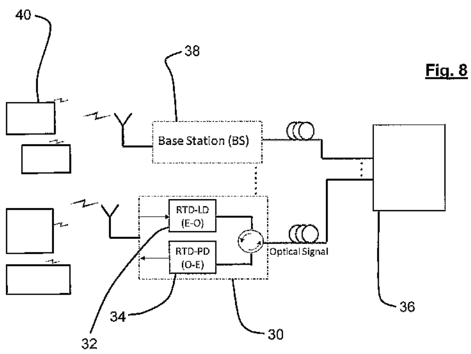

(57) **Abstract**: A wireless-optical interface device for converting a received wireless signal to a corresponding optical signal for transferring digital information from the wireless domain to the optical domain. The interface device includes an oscillator (e.g. a negative differential resistance oscillator such as a resonant tunnelling diode) capable of synchronisation with the wireless signal, and an optical output device (e.g. semiconductor laser) controllable by an output of the oscillator to provide the corresponding optical signal. The oscillator and the optical output device may be integrated on the same semiconductor chip. Also disclosed is a corresponding wireless-optical interface device for converting a received optical signal to a corresponding wireless signal for transferring digital information from the optical domain to the wireless domain.

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INTERFACES AND METHOD FOR WIRELESS-OPTICAL AND OPTICAL-WIRELESS CONVERSION

The present invention relates to telecommunications interfacing systems and methods for interfacing telecommunications signals. The invention has particular applicability to interfacing wireless signals with optical signals and/or interfacing optical signals with wireless signals.

Mobile, high data rate, wireless access networks are highly attractive for users in view of their convenience, allowing high bandwidth data communications. Such is the demand that so-called picocellular access, with wireless cells of a few meters range, is considered as a highly promising route for delivering high-bandwidth mobile access. See, for example, Sauer and Kobyakov 2007 (Sauer, M. and Kobyakov A., "Radio over fiber for pico-cellular network architectures" IEEE Journal of Lightwave Technology 25 3301-3320 2007). A key point in enabling very high data rates in such communications networks is the reduction in cell size compared with typical mobile telecommunications standards at the time of writing. Such a reduction in cell size maintains a high signal-to-noise ratio whilst limiting the transmission power to moderate levels and limiting the number of users per cell. In picocellular networks of this type, each cell may have a wireless range of only a few metres, but must typically provide an interface for onwards transmission of data to a central control station and must typically also provide an interface for wireless transmission of data received from the central control station. The transmission of data between the interface and the central control station is expected to be via optical fiber. Thus, such a system is referred to as a "radio-over-fiber" picocellular network.

In order to achieve very high data rates (1 Gb/s and higher) it is considered necessary to operate at frequencies of the order to 60 GHz, typically considered to be the millimeter wave or microwave range. However, useful communications networks may be achieved using lower frequencies, for example in the 2.4 GHz or 5 GHz bands, or lower, e.g. around 0.5 GHz. For this reason, the term "wireless signal" is used herein to encompass all such RF, microwave or millimeter wave bands.

Typical radio-over-fiber picocellular networks are expected to require, for example, hundreds of wireless-optical interface devices. The present inventors have recognized that a major challenge is to integrate wireless and optical functions on the same chip as a means of delivering low cost interfaces.

Jun et al 2007 (Dong-Hwan Jun, Sung-Won Kim, Kwang-Seok Seo, Jae-Hyung Jang, Jong-In Song, "A high-power MMIC VCO utilizing metamorphic HEMT technology" MICROWAVE AND OPTICAL TECHNOLOGY LETTERS Vol. 49, No. 9, 2221-2224 September 2007) discloses a monolithic microwave integrated circuit voltage controlled oscillator (MMIC VCO). The authors explain that this device can drive optical devices such as electro-absorption modulators, for use in radio-over-fiber wireless access infrastructure. However, such devices do not have wireless and optical functions integrated on the same chip.

It is known that a laser diode (LD) may be controlled using a negative differential resistance oscillator circuit. For example, a resonant tunnelling diode (RTD) may be allowed to produce a high frequency oscillating output to control a laser diode in an RTD-LD circuit. See, for example, Figueiredo et al 2008 ("Self-oscillation and period adding from resonant tunnelling diode-laser diode circuit" J.M.L. Figueiredo, B. Romeira, T.J. Slight, L. Wang, E. Wasige, C.N. Ironside, Electronics Letters, Volume 44, Issue 14, July 3 2008, pages 876-877); Slight et al 2006 ("Integration of a resonant tunneling diode and an optical communications laser" T.J. Slight, C.N. Ironside, C.R. Stanley, M. Hopkinson, C.D. Farmer, Photonics Technology Letters, IEEE Volume 18, Issue 14, July 2006, pages 1518-1520); and Slight and Ironside 2007 ("Investigation into the Integration of a Resonant Tunnelling Diode and an Optical Communications Laser: Model and Experiment", T.J. Slight, C.N. Ironside, IEEE J. Quant. Elec. 43, 7, 580-587, 2007), the content of each of which is hereby incorporated by reference in its entirety.

The use of resonant tunnelling diodes in optoelectronic communications systems is disclosed in WO 00/72383 and in WO 02/088834, in the context of modulation of light of wavelength 1550 nm by modulation of the absorbance characteristics of a waveguide associated with an RTD. However, these documents do not disclose the modulation of the laser itself using the output from the resonant tunnelling diode.

Additionally, US-A-5,539,761 discloses the use of a resonant tunnelling diode to modulate the output of a laser via mode locking in an optical communications system.

It is a preferred object of the present invention to provide interfaces between the wireless domain and the optical domain that can be manufactured at low cost. It is a further preferred object of the present invention to provide such interfaces that are capable of achieving improvements in speed and reliability.

Accordingly, in a first aspect, the present invention provides a wireless-optical interface device for converting a received wireless signal to a corresponding optical signal, the interface device including an oscillator capable of synchronisation with the wireless signal, and an optical output device being controllable by an output of the oscillator to provide said corresponding optical signal.

In a second aspect, the present invention provides a method of converting a wireless signal to a corresponding optical signal via a wireless-optical interface device, the interface device including an oscillator synchronised with the wireless signal, and an optical output device controlled by an output of the oscillator to provide said corresponding optical signal.

In a third aspect, the present invention provides an optical-wireless interface device for converting a received optical signal including a sub-carrier signal to a corresponding wireless signal, the interface device including an optical input and an oscillator capable of synchronisation with the sub-carrier signal, the oscillator providing in use an output to produce said corresponding wireless signal.

In a fourth aspect, the present invention provides a method of converting a sub-carrier signal in an optical signal to a corresponding wireless signal via an optical-wireless interface device, the interface device including an optical input and an oscillator synchronised with the sub-carrier signal, the oscillator providing an output to produce said corresponding wireless signal.

In a fifth aspect, the present invention provides a digital communications network providing communications links between a plurality of base stations and a control station, the base stations being linked to the control station via optical fiber links, each base station providing a cell for wireless access by users, and each base station providing a wireless-optical interface and an optical-wireless interface, wherein:

(a) the wireless-optical interface allows conversion of a received wireless signal from a user to a corresponding optical signal for forwarding to the control station, the interface including an oscillator capable of synchronisation with the wireless signal, and an optical output device being controllable by an output of the oscillator to provide said corresponding optical signal; and

(b) the optical-wireless interface allows conversion of a received optical signal from the control station including a sub-carrier signal to a corresponding wireless signal for sending to the user, the interface including an optical input and an oscillator capable of synchronisation with the sub-carrier signal, the oscillator providing in use an output to produce said corresponding wireless signal.

Preferred and/or optional features of the invention are set out below. These may be combined singly or in any combination with any aspect of the invention, unless the context demands otherwise.

Synchronisation of oscillators is a widely studied and well-understood phenomenon. Preferably in the present invention, the synchronisation between the wireless signal and the oscillator is used to transfer digital information from the wireless domain to the optical domain. Similarly, the synchronisation between the sub carrier signal and the oscillator is used to transfer digital information from the optical domain to the electronic domain.

The use of synchronisation in this way can allow the injection of a weak periodic signal to cause locking (synchronisation) of the oscillator. In other words, the oscillator locks to the same frequency as the injected signal with a fixed phase difference. Most current wireless communication standards use phase shift keying (PSK) to encode digital information and so, because of the fixed phase relationship, if the wireless signal can be used as a weak synchronisation signal for an oscillator modulating an optical signal then the digital information encoded in the phase of a wireless signal can transferred to the phase of the sub-carrier in the optical signal. It is considered that synchronisation can occur even if the power of the weak injected signal is up to 53dB less than the output power from the oscillator (see, for example, B. Razavi, "A study of injection locking and pulling in oscillator" IEEE Journal of Solid-Sate circuits 39 1415-1424 2004).

Thus, it is preferred that the wireless signal includes digital information encoded via phase shift keying.

Various phase shift keying (PSK) scheme may be used. For example, binary phase shift keying (BPSK) may be used. Alternatively, more complex phase shift keying schemes may be used, such as quadrature phase shift keying (QPSK) or higher order PSK. The phase shift keying may be differential phase shift keying, in order to simplify the decoding process.

Preferably, the optical output device is a semiconductor laser or an optical modulator. Where the optical output device is a semiconductor laser, preferably it is an edge-emitting or a vertical-external-cavity surface emitting laser.

The frequency or wavelength of the optical signal is not particularly limited. The present inventors consider in particular that synchronisation properties of the device is substantially independent of the wavelength of the optical signal. For example, the wavelength of the optical signal may conveniently be in any optical or near-optical wavelength, including infrared and ultraviolet wavelengths. For example, wavelengths of 1550 nm, 1300 nm, 850 nm and 790 nm are considered to work successfully with the device.

Preferably, the oscillator is a negative differential resistance oscillator. For example, a resonant tunnelling diode is a suitable oscillator.

Preferably the frequency of the wireless signal is at least 500 MHz. More preferably, the frequency of the wireless signal is at least 600 MHz, at least 700 MHz, at least 800 MHz of at least 900 MHz. For example, the frequency of the wireless signal may be in the range 900 MHz to 2.5 GHz (or possibly up to 5 GHz). Preferably the frequency of the wireless signal is at most 100 GHz. More preferably, the frequency of the wireless signal is at most 90 GHz, at most 80 GHz, at most 70 GHz, or at most 60 GHz. The present inventors consider that the use of higher frequencies has the advantage of providing significantly higher data rates. However, the advantage of using lower frequencies in the ranges mentioned above is the ability to use or modify existing communications protocols and hardware, for example based on the well-known IEEE 802.11 family of standards for wireless local area network computer communications.

Preferably, in use, the power of the wireless signal received at the device is relatively low. This is preferred in view of the fact that the device can still provide reliable interfacing between the received wireless signals and the optical output, which allows the communications network to operate efficiently at relatively low power. For example, the received wireless signal may have a power of -20 dBm or less (where 0 dBm (or 0 dBmW) is equivalent in power to 1 mW). More preferably, the received wireless signal may have a power of -25 dBm or less, -30 dBm or less, -35 dBm or less, or -40 dBm or less.

Preferably, in the first, second and fifth aspects, in the wireless-optical interface, the oscillator and the optical output device are integrated on the same semiconductor chip.

Preferably, in the third, fourth and fifth aspects, in the optical-wireless interface, the optical input leads to a photodetector for providing a corresponding electrical signal for the oscillator. However, in some embodiments such a photodetector may be unnecessary. In this case, it is possible for the oscillator itself to provide an electronic response when illuminated with the optical signal. Certain resonant tunnelling diodes, for example, are formed using photoconductive semiconductor alloys and so provide at least a weak injected signal to the resonant tunnelling diode when illuminated with the optical signal. Where a photodetector is provided, preferably it is provided integrated on the same chip as the oscillator.

Preferably, the device includes at least one antenna for receiving and/or transmitting said wireless signal.

Preferred embodiments of the present invention will now be set out, with reference to the accompanying drawings, in which:

Fig. 1 shows an RTD-LD optoelectronic interface characterization setup diagram, according to an embodiment of the present invention.

Fig. 2 shows experimental synchronization of laser diode output for two DC bias at 1/4 (Fig. 2(a)) and 1/3 (Fig. 2(b)) of a 3 GHz broadcasted signal for an embodiment of the present invention.

Fig. 3 shows a simplified frequency synchronization map given by an implemented Liénard's model for a range of DC bias for an embodiment of the present invention.

Fig. 4 shows a simulation of a RTD-LD OVCO designed to lock to a 3 GHz broadcasted signal, in accordance with an embodiment of the present invention.

Fig. 5 shows the measured spectra of electrical outputs for self-sustained oscillations around 600 MHz and phaselocking by wireless injection for an RTD-LD for use in an embodiment of the present invention.

Fig. 6 shows the measured spectra of electrical outputs for self-sustained oscillations around 1.8 GHz (2^{nd} harmonic) and phaselocking by wireless injection for an RTD-LD for use in an embodiment of the present invention.

Fig. 7A shows the frequency spectrum for the injected microwave signal at 600 MHz modulated by a sub-carrier signal at 1 MHz phase shifted by 90°, and Fig. 7B shows the corresponding frequency spectrum for the optical output of a device according to an embodiment of the invention.

Fig. 8 shows a schematic illustration of a communications network according to an embodiment of the invention.

In the discussion that follows, further preferred and/or optional features are set out that may be combined in any combination with any of the aspects of the invention.

Recent work has shown that a RTD can be integrated with a LD (see Slight et al 2006, above) and that a hybrid (separate RTD and LD chips) RTD-LD circuit operates as a self-oscillating circuit and can work as an optoelectronic voltage controlled oscillator (OVCO) that can be synchronized to an external signal (see Figueiredo et al 2008, above). The RTD-LD is a type of Liénard's oscillator which is a generalization of the Van der Pol oscillator, and the theory of the synchronization of these oscillators is well established and understood by the skilled person (see, for example, the textbook "Synchronization: a universal concept in nonlinear sciences" Pikovsky A., Rosenblum M., Kurths J., Cambridge University Press, 2001).

The present inventors show here experimentally that the RTD-LD can synchronize to a wireless signal. Furthermore it is possible to show from the theory of the Liénard's oscillator that the phase of the radio frequency subcarrier in the optical output from the laser follows the phase of the wireless signal that is injected into the RTD-LD circuit. Since the digital information can be encoded on the wireless using phase shift keying (PSK) then the optical output from the synchronized RTD-LD contains the digital PSK information present in the wireless signal. This is a novel concept and it will require some modification to the network protocols and architectures that are currently under consideration for such communications networks. However, the RTD-LD does have the considerable advantage that the microwave and optical functions can be integrated in a single OEIC chip rather than having separate Monolithic Microwave Integrated Circuits (MMIC) chips and optical chips and, as is normally the case with integration, we can expect not only a reduction in cost but also an increases in speed and reliability.

The microwave-optical interface circuit has an electric-to-optic (E/O) converter, the OEIC (optoelectronic integrated circuit) RTD-LD. A detailed description and operating principle of the RTD-LD E/O converter can be found in Figueiredo et al 2008 ("Self-oscillation and period adding from resonant tunnelling diode-laser diode circuit" J.M.L. Figueiredo, B. Romeira, T.J. Slight, L. Wang, E. Wasige, C.N. Ironside, Electronics Letters, Volume 44, Issue 14, July 3 2008, pages 876-877), the content of which is incorporated herein by reference in its entirety.

Fig. 1 shows a schematic view of a RTD-LD optoelectronic interface characterization setup that includes an electrical amplifier and patch antennas designed to operate at 3 GHz, for transmission of a 16 dBm (about 1.4 V) signal over a distance of a few meters.

An RTD-LD electro-optical converter 10 is connected to patch antenna 12 via bias tee 14. In the view shown in Fig. 1, patch antenna 12 receives an RF signal from RF signal generator 16. The output from RTD-LD E/O converter 10 is sent to a measurement set-up, including photodetector 18, the output of which is amplified in the frequency range 0.5-6 GHz and analysed using an oscilloscope or spectrum analyzer 22.

Without external excitation the RTD-LD circuit operates as an autonomous self-sustaining optoelectronic voltage controlled oscillator (OVCO) between 563 MHz and 997

MHz, depending on bias voltage. This is the oscillator's natural frequency range. In the presence of the wireless signal it synchronizes to the wireless frequency, modulating the laser diode with the wireless signal.

Fig. 2 shows experimental synchronization of the laser diode output for two DC bias at 1/4, Fig. 2(a), and 1/3, Fig. 2(b), of a 3 GHz broadcasted signal. A broadcast signal $V_{AC}\sin(2\pi f_{in}t)$ with V_{AC} = 1.4 V and f_{in} = 3 GHz was received by the antenna connected to the RTD-LD, for DC bias 3.62 V (Fig. 2(a)) and 3.94 V (Fig. 2(b)). Fig. 2(a) shows the laser output showing frequency locking at 0.75 GHz. Fig. 2(b) shows the laser output showing frequency locking at 1.0 GHz. The frequency locking can also be controlled by tuning both the bias voltage and power of broadcasted signal.

We note here that the RTD-LD wireless-optical interfaces described here are not necessarily restricted to 1550 nm wavelengths, and can be used in other communications bandwidths including optical fibre systems operating at 850 nm and 1300 nm. Although RTD-LD circuit operation is dependent on laser diode characteristics (parasitic capacitance and resistance, threshold current, etc.) its synchronization properties are independent of laser diode wavelength. In fact, the RTD-LD interfaces under consideration were tested at 790 nm and 1550 nm laser diode wavelengths showing similar wireless to optical synchronization results.

It is of interest to consider here the theory of Liénard's wireless driven oscillator. The OEIC RTD-LD driven by a wireless carrier signal can be described by the following two first-order nonlinear coupled differential equations, equivalent to a Liénard's driven oscillator:

$$\dot{V} = \frac{1}{C}[I - F(V)] \qquad (1)$$

$$\dot{I} = \frac{1}{L}[V_{DC} - RI - V + V_{AC}\sin(2\pi f_{in}t + \phi_m(t))], \qquad (2)$$

where $V_{AC}\sin(2\pi f_{in}t) = c(t)$ is the wireless carrier signal and $\varphi_m(t)$ is the phase modulation function. The optoelectronic model is completed with the laser diode rate equations:

$$\dot{N} = \frac{I}{q\vartheta} - \frac{N}{\tau} - g_0(N - N_0)\frac{S}{1 + \varepsilon S} \qquad (3)$$

$$\dot{S} = g_0(N - N_0)\frac{S}{1 + \varepsilon S} - \frac{S}{\tau_p} + \frac{\beta N}{\tau} \qquad (4)$$

$$\frac{S}{P_f} = \frac{\Gamma \tau_p \lambda_0}{\vartheta \eta h c}. \qquad (5)$$

Fig. 3 shows a simplified simulated frequency synchronization map given by the implemented Liénard's model for a range of DC bias. The hatched areas in the map correspond to the main synchronisation regions of optical outputs with the wireless signal and the white areas correspond to unsynchronised ones. As shown in Fig. 3, the RTD-LD can lock to the fundamental of a broadcasted signal if close to the oscillator's natural frequency, or to some subharmonics of broadcasted signal, depending on the bias voltage and the broadcasted frequency. The model gives a good prediction of the experimental results presented in Fig. 2.

The Liénard's optoelectronic model, equations (1-5), anticipates that frequency and phase synchronization is achievable with an autonomous RTD-LD OVCO with natural frequency close to the broadcasted frequency. Fig. 4 shows a simulation of a RTD-LD OVCO designed to lock to a 3 GHz broadcasted signal with amplitude as low as 100 mV. The laser output is simulated and showed frequency locking to a broadcasted carrier c(t) with f_{in} = 3 GHz and V_{AC} = 100 mV. Fig. 4 shows that the laser output follows the shifts (φ_m = 0 or π) of the broadcasted signal injected into the RTD-LD through the patch antenna and locks with the broadcasted signal injected into the RTD-LD after about 1.5 periods of the wireless carrier signal. As the skilled person immediately understands, this behaviour can be used for PSK digital modulation.

Thus, the inventors have experimentally demonstrated a period adding synchronization between a wireless signal and an optical signal with a RTD-LD hybrid circuit. Using

Liénard's oscillator theory it has been shown that radio sub-carrier of optical signal follows the phase modulation of the wireless signal. The RTD can be integrated with the LD and so the integrated RTD-LD OEIC can form a single chip platform for a low cost microwave/photonics interface device.

The inventors provide further experimental results on phase-locking an noise reduction in an RTD-LD oscillator for use in embodiments of the present invention.

In this embodiment a microwave-optical interface configuration comprises a resonant tunnelling diode (RTD) integrated with a laser diode (LD) operating at around 1550 nm wavelength. When the circuit is operating in the self-oscillating mode and wireless signals are injected, the circuit is capable of phase-locking at the fundamental and harmonic oscillating frequencies, as discussed above. The RTD-LD responds to the wireless signals and gives rise to the production of locked signals in the RTD-LD electrical and optical outputs with significant noise reduction near the locked frequency.

The microwave-optical interface circuit consists of an RTD-LD oscillator as discussed above. The setup of the RTD-LD optoelectronic interface includes patch antennas for directional wireless emission-reception. When biased in the negative differential resistance region and without external excitation, the RTD-LD operates as an autonomous self-sustaining oscillator, changing natural frequency from 483 MHz up to 643 MHz, depending on bias voltage. Below are presented the wireless locking characteristics of the fundamental oscillations and the 2^{nd} harmonic when the circuit is biased to produce relaxation oscillations around 600 MHz. Note that the embodiment described here differs from that described with respect to Fig. 2 in that it operates with a slightly different tuning range.

The wireless injection power was varied to show the locking phenomena. A noticeable locking phenomenon with significant phase noise reduction appeared at wireless injection powers of -30 dBm and lower. Phase locking at the fundamental frequency was observed in the optical output for injected powers even lower than -40 dBm and with significant noise reduction.

Fig. 5 shows the measured spectra of electrical outputs for self-sustained oscillations around 600 MHz and phaselocking by wireless injection. As shown in Fig. 5, the relaxation oscillations produce a broad frequency spectrum output, showing a gradual decrease of spectral power density. When the wireless signal at 600 MHz is injected into the RTD LD, a stable frequency locking is observed. The phase noise of the self-sustained oscillations is reduced by up to about 35 dB at up to about a 10 kHz offset due to the external injection. Under these conditions the frequency-locked bandwidth frequency was measured to be 0.5%. Although not shown in this figure, it is also possible to display in colour the spectrum surveillance of self-oscillations and wireless phase-locked signals in the laser diode output relative to a carrier frequency of 600 MHz. The graph of Fig. 5 shows the fundamental self-oscillation peak at 600 MHz and the phase-locked peak in the laser diode output when a wireless signal of about -25 dBm power is injected. The phase noise is reduced by about 35 dB at a 10 kHz offset of the carrier frequency. Phase locking was observed in the optical output for injected powers at around -40 dBm with significant noise reduction. Resolution bandwidth and video bandwidths are 1 kHz. Under these conditions the frequency-locked bandwidth was measured to be 0.5%.

Similar results are now presented for when the wireless frequency is the same as the 2nd harmonic of self-oscillations at 600 MHz, in this case, 1.8 GHz. Fig. 6 shows the spectrum of the locked 2nd harmonic and the corresponding self-sustained 2nd harmonic at around 1.8 GHz under similar conditions to Fig. 5 except that here the wireless signal has a frequency of 1.8 GHz and power of -40 dBm. From a comparison between the spectra we calculate a phase noise reduction of about 25 dB at a 10 kHz offset of the carrier frequency and a tuning frequency bandwidth of 0.4%. The resolution bandwidth and video bandwidths are 1 kHz. We note that because the injected power is so low, the frequency-locked bandwidth tuning in these conditions is much lower. Increasing the injection power higher than -20 dBm, frequency-locked bandwidths up to 5% in the electrical output are also observed in the optical output. The present measurements of noise reduction are limited by the internal noise of the spectrum analyser (HP 8564A).

Thus, there has been experimentally demonstrated phase-locked operation between wireless and self-sustained oscillations on a RTD-LD circuit. Although the experimental results presented here are addressed to the electrical output, similar locking results are expected in the laser diode output. When the circuit is wireless-locked in frequency, the spectral power densities near the locked oscillation frequency are observed to be significantly reduced, showing that the noise is reduced by more than 20 dB at 1 MHz offset, compared with the RTD-LD harmonic self-sustained oscillations. The locked oscillation frequency is tunable by adjusting the resonant frequency using the DC bias or the wireless frequency signal and a locking range up to 90 MHz was measured, with a tuning bandwidth of 5% at the centre frequency of 1.8 GHz. The results of Figs. 5 and 6 demonstrate further that the laser diode output can be locked with very low injected powers (less than -40 dBm) and with a significant phase noise reduction. Because the injected power is so low the frequency-locked bandwidth tuning in these conditions is much lower (about 0.5%) than with higher power injected signals.

We now present phase-locking results when the broadcasted microwave signal at 600 MHz is phase modulated by a subcarrier sine wave at 1 MHz. Fig. 7A shows the broadcasted signal phase modulated by a sub-carrier signal with a phase shift of 90°. The injected power was about -30 dBm. Fig. 7B shows the laser diode output phase-locked with the broadcasted signal, showing the same modulation features of the injected signal with the same sidebands at 1 MHz offset of the carrier signal. The phase modulation was tested at several phase angles using sinusoidal, quadratic and triangle waveforms. The laser output was observed to clearly follow the modulation of the broadcasted carrier signal in the different modulation conditions and with low injected powers.

Based on the discussion above, it is clear that in one embodiment the present invention provides an interface using a hybrid RTD-LD. However, in a preferred embodiment, an integrated RTD-LD is used. The reason for this is the improved efficiency, speed, reliability and manufacturing costs (when manufactured on a large scale) that integrated components can achieve.

In the embodiments of the invention. the RTD-LD circuit works as an optoelectronic voltage controlled oscillator that can be synchronized to an external signal. The RTD-LD is a type of Lienard's oscillator which is a generalization of the Van der Pol oscillator and the theory of the synchronization of these oscillators is well established. As shown and discussed above, the RTD-LD can synchronize to a wireless signal and the phase of the radio frequency sub-carrier in the optical output from the laser follows the phase of the wireless signal that is injected into the RTD-LD circuit.

In the embodiments discussed so far, attention has concentrated on the wireless-to-optical interface. However, a full wireless/optical interface require optical to electrical (O-E) conversion as well. The present inventors have realised that synchronisation can also be used for the O-E function. A self oscillating RTD can be illuminated with an optical signal that has a microwave sub-carrier PSK encoded. The self-oscillating RTD synchronises to the phase of the optical signal and the RTD oscillator is coupled to an antenna and thereby radiate a wireless signal that is PSK encoded. The RTD-LD synchronises to the optical signal because the semiconductor alloys that make up the RTD are photoconductive and so when illuminated there is a weak injected signal present in the RTD to which the oscillation will lock.

In an alternative embodiment of the optical-to-wireless interface, a photodetector is provided to receive the optical signal with a microwave sub-carrier PSK encoded. The photodetector thus provides an injected electrical signal to the RTD corresponding to the optical signal, to which the RTD synchronises.

In a preferred implementation of the invention, as illustrated in Fig. 8, there is provided a communications network using Radio over Fiber (RoF) communications combining in Base Station 30 (pico-cell) an RTD-LD E-O converter 32 and an RTD-PD (photodetector) O-E converter 34. In this network a Central Station 36 (CS) is connected to numerous functionally simple Base Stations 38 (BSs) via optical fibre. Each Base Station is connectable via RF with mobile communications devices (e.g. laptops) 40.

The optoelectonic integrated RTD-LD circuits are used in a wireless access network where the Central Station 36 (CS) is connected to numerous functionally simple Base Stations 30, 38(BSs) via optical fiber. The main function of BS combining RTD-LD wireless/optical interface is to convert optical signal to wireless one and vice versa. Almost all processing including modulation, demodulation, coding, routing is performed at the CS. Fig. 8 shows a general Radio over Fiber architecture (Radio over Fiber refers to a fiber optic link where the optical signal is modulated at radio frequencies and transmitted via the optical fiber). At a minimum, an RoF link consists of all the hardware required to impose an RF signal on an optical carrier, the fiber optic link, and the hardware required to recover the RF signal from the carrier. Together with small cell size (picocell), RoF technology employing RTD-LD RF/photonic interface devices can provide much higher capacity than conventional wireless networks at microwave bands such as 2.4 or 5 GHz. In the RoF network the pico-cell base station consists of a microwave-optical interface circuit combining an electric-to-optic (E-O) converter, the OEIC RTD-LD, and an optic-to-electric (O-E) converter, OEIC RTD-PD photo-detector, where the OEIC RTD-LD provides the up-link access and the OEIC RTD-PD provides the down-link access.

Preferred embodiments of the invention have been described by way of example. Modifications of these embodiments, further embodiments and modifications thereof will be apparent to the skilled person on reading this disclosure and as such are within the scope of the present invention.

CLAIMS

1. A wireless-optical interface device for converting a received wireless signal to a corresponding optical signal, the interface device including an oscillator capable of synchronisation with the wireless signal, and an optical output device being controllable by an output of the oscillator to provide said corresponding optical signal.

2. A device according to claim 1 wherein the synchronisation between the wireless signal and the oscillator is used to transfer digital information from the wireless domain to the optical domain.

3. A device according to claim 1 or claim 2 wherein the wireless signal includes digital information encoded via phase shift keying.

4. A device according to any one of claims 1 to 3 wherein the optical output device is a semiconductor laser or an optical modulator.

5. A device according to claim 4 wherein the optical output device is an edge-emitting or a vertical-external-cavity surface emitting semiconductor laser.

6. A device according to any one of claims 1 to 5 wherein the oscillator is a negative differential resistance oscillator.

7. A device according to claim 6 wherein the oscillator is a resonant tunnelling diode.

8. A device according to any one of claims 1 to 7 wherein the frequency of the wireless signal is at least 500 MHz and at most 100 GHz.

9. A device according to any one of claims 1 to 8 wherein, in use, the power of the wireless signal received at the device is -20 dBm or less.

10. A device according to any one of claims 1 to 9 wherein the oscillator and the optical output device are integrated on the same semiconductor chip.

11. A device according to any one of claims 1 to 10 wherein the device includes at least one antenna for receiving and/or transmitting said wireless signal.

12. A method of converting a wireless signal to a corresponding optical signal via a wireless-optical interface device, the interface device including an oscillator synchronised with the wireless signal, and an

optical output device controlled by an output of the oscillator to provide said corresponding optical signal.

13. An optical-wireless interface device for converting a received optical signal including a sub-carrier signal to a corresponding wireless signal, the interface device including an optical input and an oscillator capable of synchronisation with the sub-carrier signal, the oscillator providing in use an output to produce said corresponding wireless signal.

14. A device according to claim 13 wherein the optical input leads to a photodetector for providing a corresponding electrical signal for the oscillator.

15. A device according to claim 13 wherein the oscillator itself to provides an electronic response when illuminated with the optical signal.

16. A method of converting a sub-carrier signal in an optical signal to a corresponding wireless signal via an optical-wireless interface device, the interface device including an optical input and an oscillator synchronised with the sub-carrier signal, the oscillator providing an output to produce said corresponding wireless signal.

17. A digital communications network providing communications links between a plurality of base stations and a control station, the base stations being linked to the control station via optical fiber links, each base station providing a cell for wireless access by users, and each base station providing a wireless-optical interface and an optical-wireless interface, wherein:

(a) the wireless-optical interface allows conversion of a received wireless signal from a user to a corresponding optical signal for forwarding to the control station, the interface including an oscillator capable of synchronisation with the wireless signal, and an optical output device being controllable by an output of the oscillator to provide said corresponding optical signal; and

(b) the optical-wireless interface allows conversion of a received optical signal from the control station including a sub-carrier signal to a corresponding wireless signal for sending to the user, the interface including an optical input and an oscillator capable of synchronisation with the sub-carrier signal, the oscillator providing in use an output to produce said corresponding wireless signal.

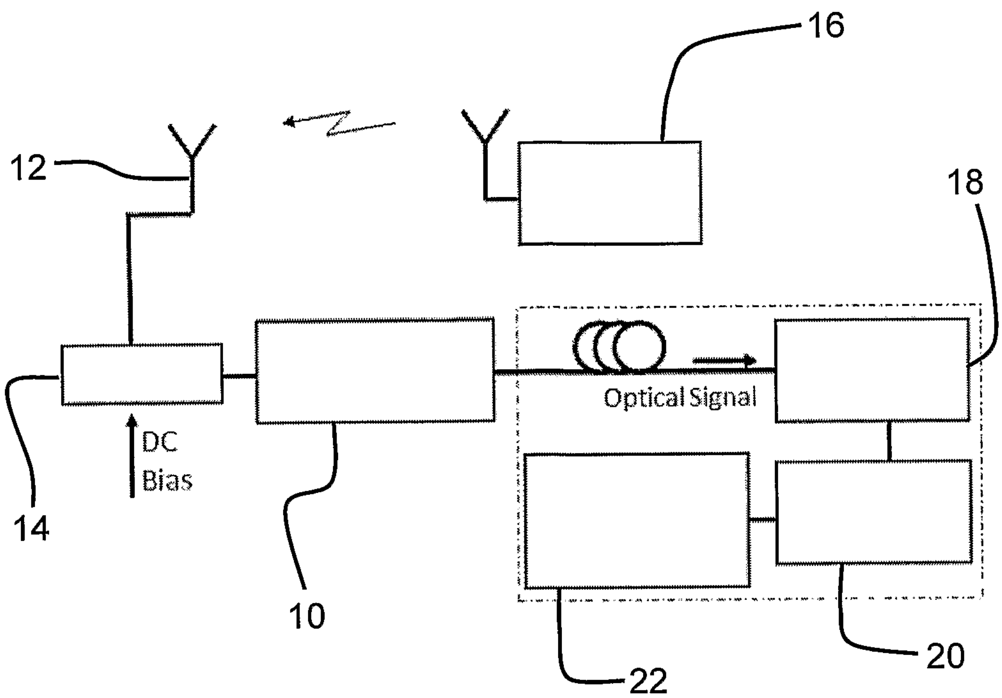
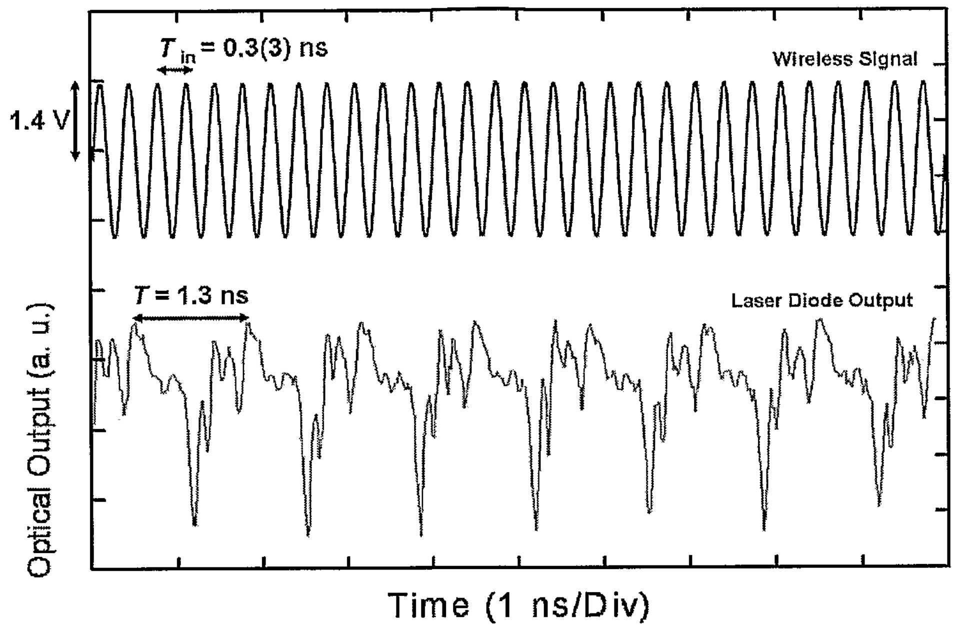
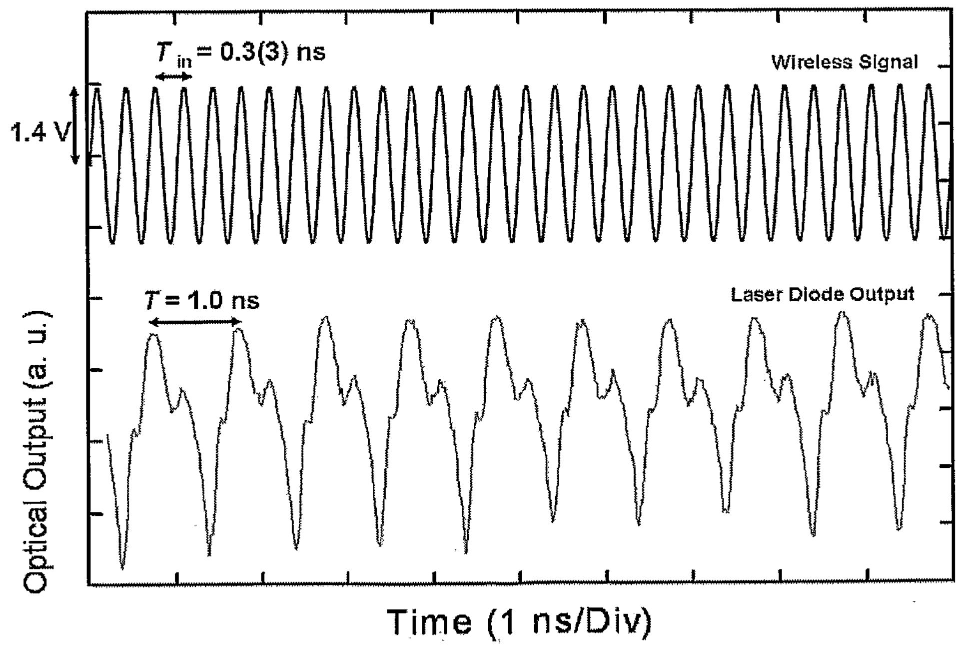


Fig. 1


T in = 0.3(3) ns
Wireless Signal
1.4 V
T = 1.3 ns
Laser Diode Output
Optical Output (a. u.)
Time (1 ns/Div)

(a)


T in = 0.3(3) ns
Wireless Signal
1.4 V
T = 1.0 ns
Laser Diode Output
Optical Output (a. u.)
Time (1 ns/Div)

(b)

Fig. 2

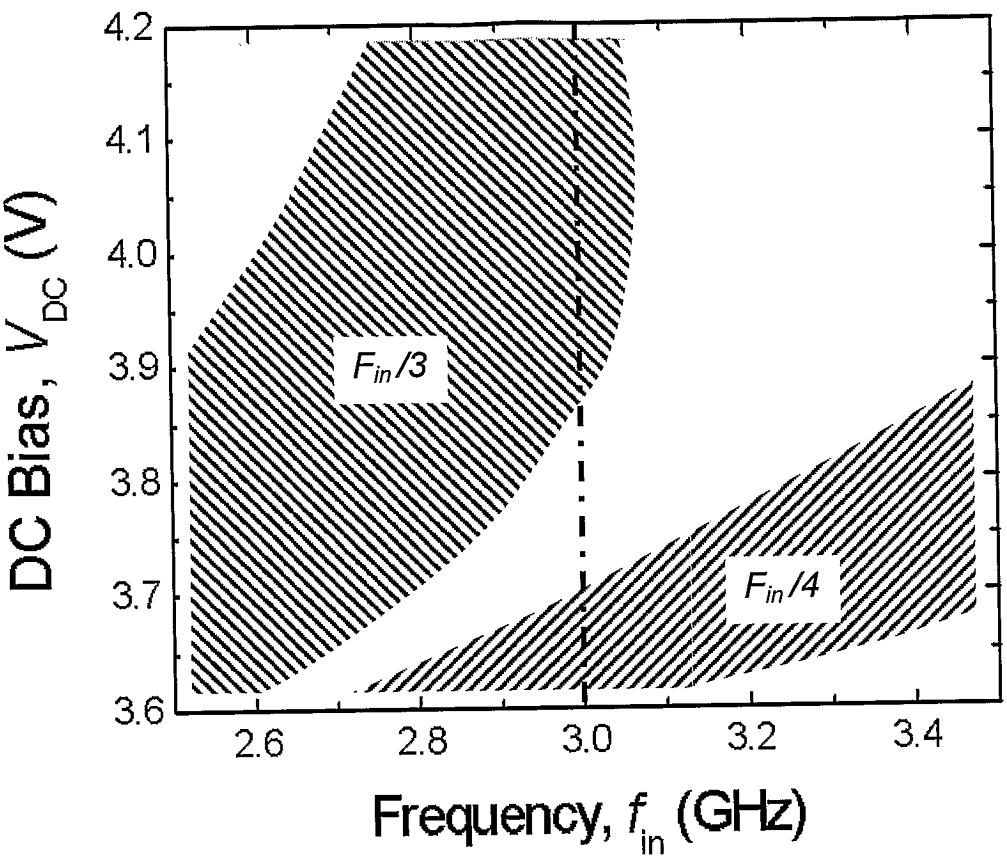

4.2
4.1
4.0
3.9
3.8
3.7
3.6
DC Bias, V_{DC} (V)
$F_{in}/3$
$F_{in}/4$
2.6
2.8
3.0
3.2
3.4
Frequency, f_{in} (GHz)

Fig. 3

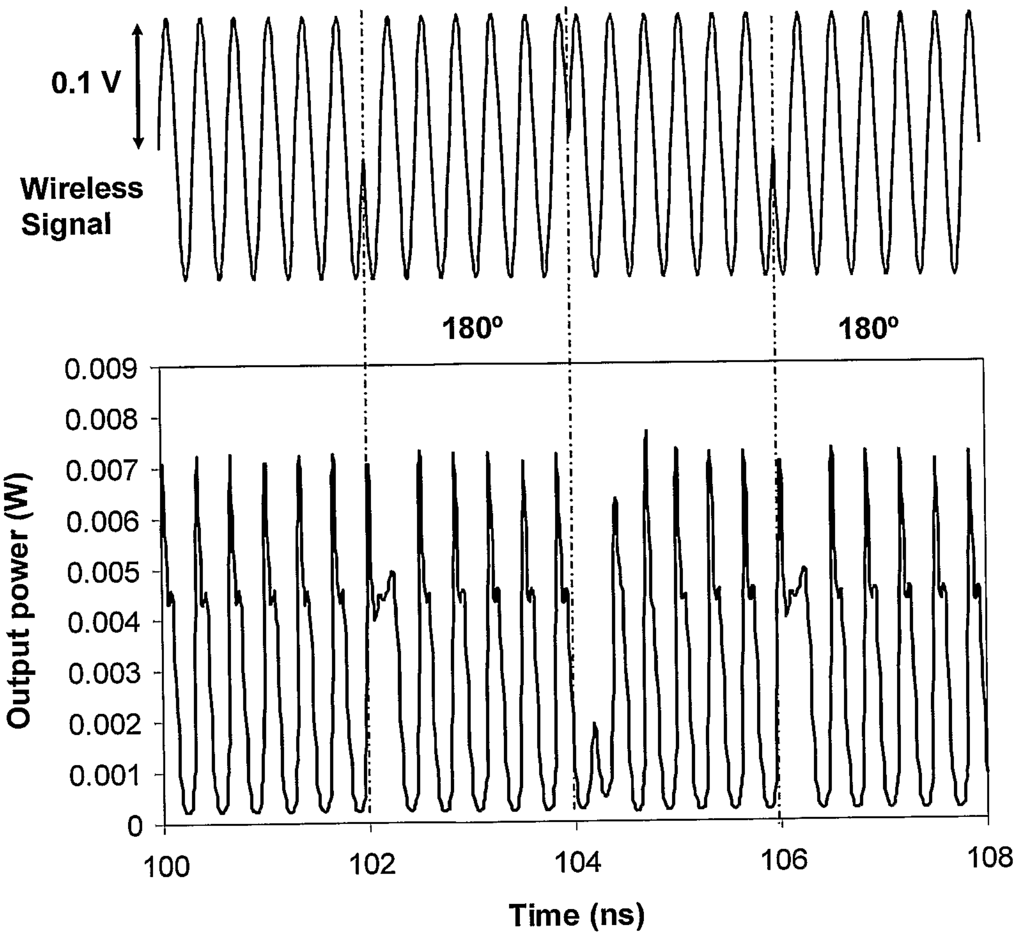

0.1 V
Wireless Signal
180°
180°
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
Output power (W)
100
102
104
106
108
Time (ns)

Fig. 4

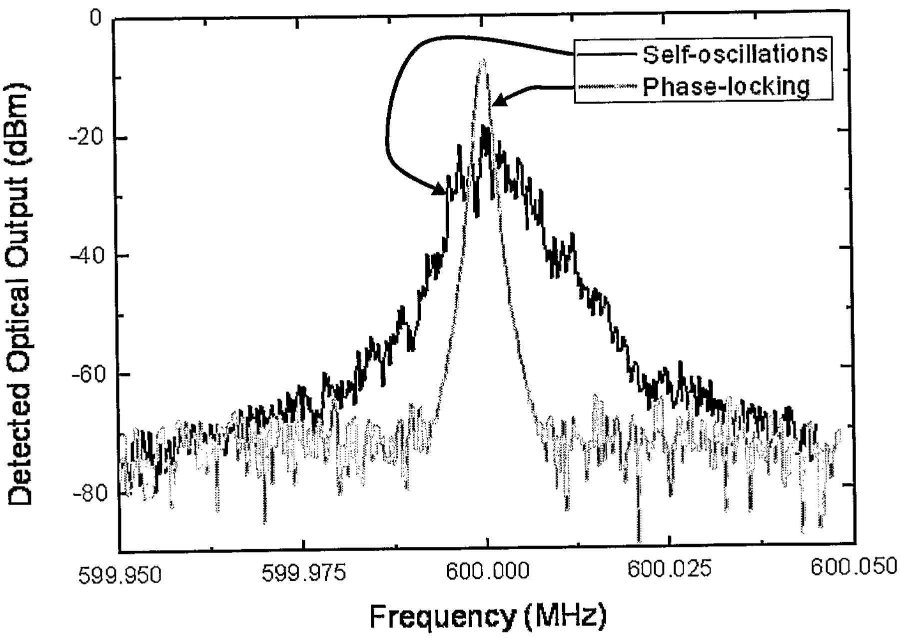

Self-oscillations
Phase-locking
Detected Optical Output (dBm)
0
-20
-40
-60
-80
599.950
599.975
600.000
600.025
600.050
Frequency (MHz)

Fig. 5

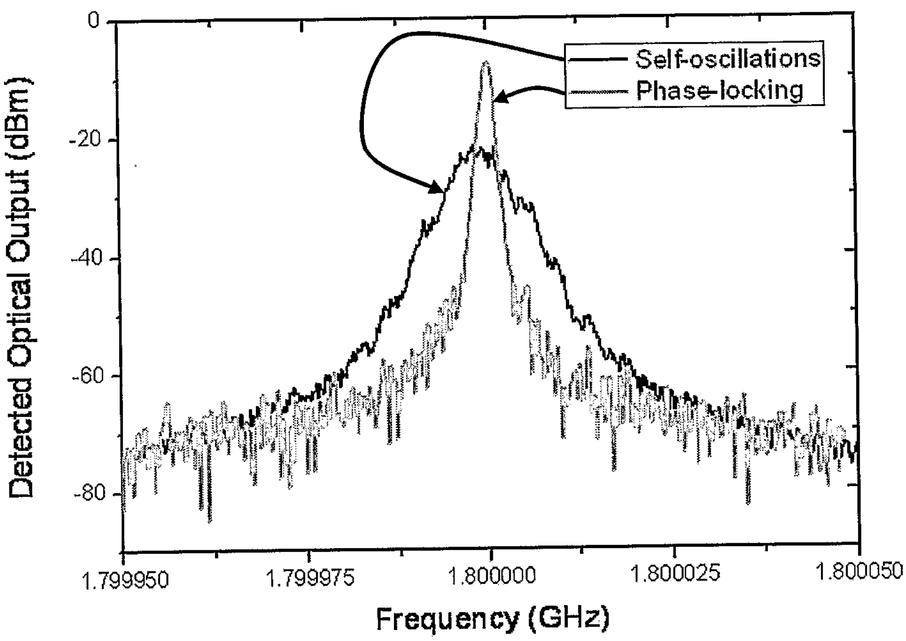

Self-oscillations
Phase-locking
Detected Optical Output (dBm)
0
-20
-40
-60
-80
1.799950
1.799975
1.800000
1.800025
1.800050
Frequency (GHz)

Fig. 6

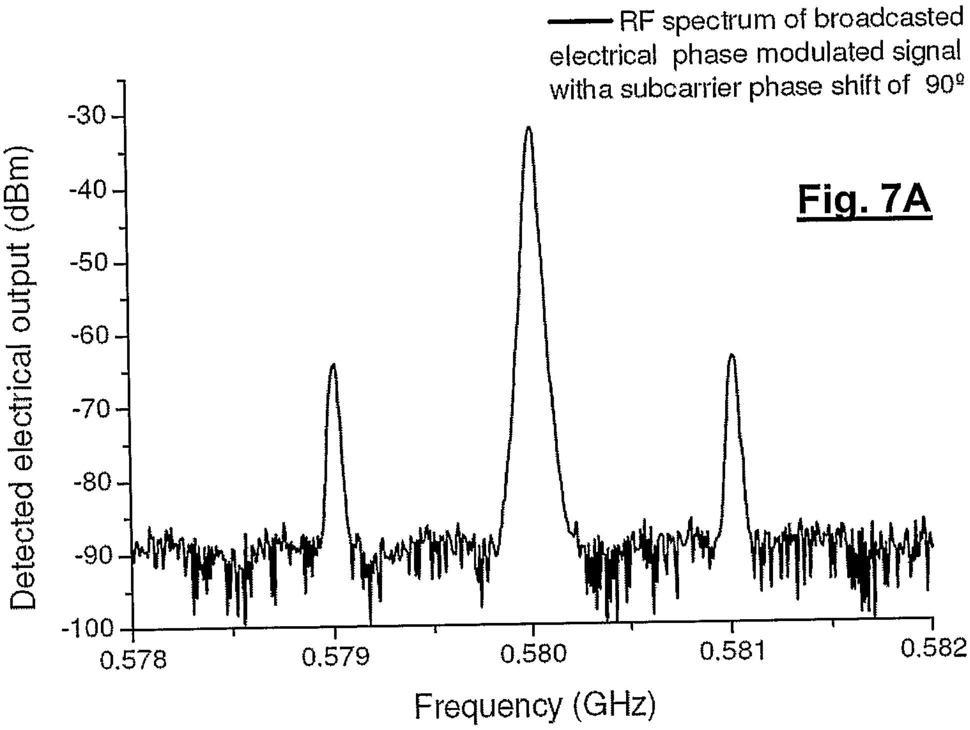

RF spectrum of broadcasted electrical phase modulated signal witha subcarrier phase shift of 90º
Detected electrical output (dBm)
-30
-40
-50
-60
-70
-80
-90
-100
0.578
0.579
0.580
0.581
0.582
Frequency (GHz)

Fig. 7A

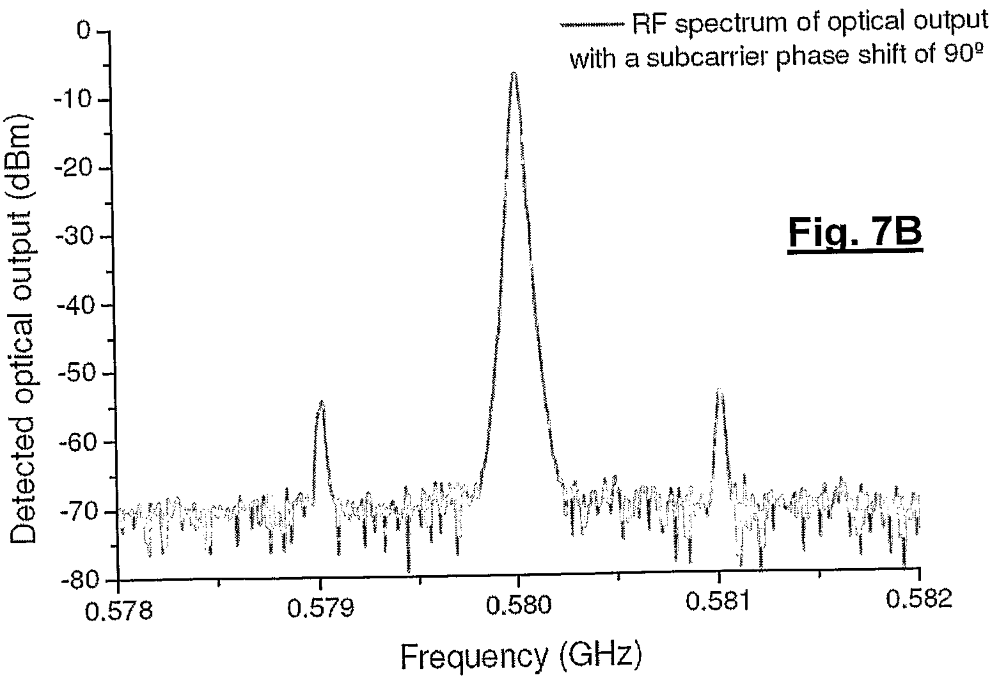

RF spectrum of optical output with a subcarrier phase shift of 90º
Detected optical output (dBm)
0
-10
-20
-30
-40
-50
-60
-70
-80
0.578
0.579
0.580
0.581
0.582
Frequency (GHz)

Fig. 7B

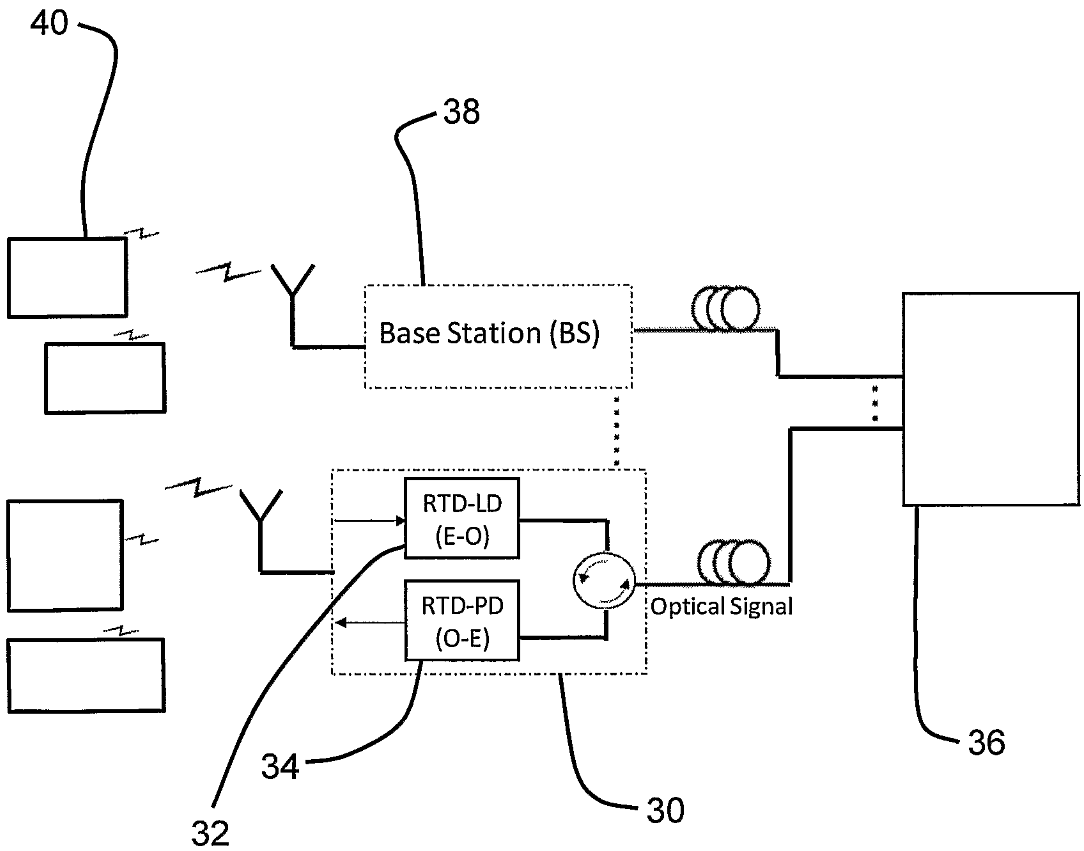

40
38
Base Station (BS)
RTD-LD
(E-O)
RTD-PD
(O-E)
Optical Signal
36
34
30
32

Fig. 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2009/002637

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04B10/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 00/72383 A (UNIV GLASGOW [GB]; IRONSIDE CHARLES NORMAN [GB]; STANLEY COLIN ROY [GB) 30 November 2000 (2000-11-30) cited in the application abstract page 1, lines 3-12 page 3, lines 4-27 page 4, lines 15-24 page 5, line 11 - page 6, line 32 page 10, lines 2-29 figures 1(A),1(B) ----- -/--	1-4,6-17

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 January 2010	03/02/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Rolan Cisneros, E

Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CALADO J J N ET AL: "Modeling of a resonant tunneling diode optical modulator" MICROWAVE AND OPTOELECTRONICS, 2005 SBMO/IEEE MTT-S INTERNATIONAL CONF ERENCE ON JULY 2005, PISCATAWAY, NJ, USA,IEEE, 20 July 2005 (2005-07-20), pages 96-99, XP010885305 ISBN: 978-0-7803-9341-7 the whole document	1-4,6-17
X	FIGUEIREDO J M L ET AL: "High speed electroabsorption modulator by integration of a RTD with an optical waveguide" HIGH PERFORMANCE ELECTRON DEVICES FOR MICROWAVE AND OPTOELECTRONIC APP LICATIONS, 1997. EDMO. 1997 WORKSHOP ON LONDON, UK 24-25 NOV. 1997, NEW YORK, NY, USA,IEEE, US, 24 November 1997 (1997-11-24), pages 352-357, XP010275363 ISBN: 978-0-7803-4135-7 the whole document	1-4,6-17
X	CALADO J J N ET AL: "Modelling of a modulator based on resonant tunnelling diode switching" ELECTRON DEVICES FOR MICROWAVE AND OPTOELECTRONIC APPLICATIONS, 2004. EDMO 2004. 12TH INTERNATIONAL SYMPOSIUM ON KRUGER NATIONAL PARK, SOUTH AFRICA NOV. 8-9, 2004, PISCATAWAY, NJ, USA,IEEE, 8 November 2004 (2004-11-08), pages 39-42, XP010781755 ISBN: 978-0-7803-8574-0 the whole document	1-4,6-17
X	WO 02/088834 A (UNIV GLASGOW [GB]; IRONSIDE CHARLES NORMAN [GB]; FIGUEIREDO JOSE LONGR) 7 November 2002 (2002-11-07) cited in the application abstract pages 1-3	1-4,6-12
Y	MICHAEL SAUER ET AL: "Radio Over Fiber for Picocellular Network Architectures" JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 25, no. 11, 1 November 2007 (2007-11-01), pages 3301-3320, XP011198536 ISSN: 0733-8724 cited in the application the whole document	1-12

-/--

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	FIGUEIREDO J M L ET AL: "Self-oscillation and period adding from resonant tunnelling diode-laser diode circuit" THE INSTITUTION OF ENGINEERING AND TECHNOLOGY. JOURNAL,, vol. 44, no. 14, 3 July 2008 (2008-07-03), pages 876-878, XP006031365 ISSN: 1350-911X cited in the application the whole document -----	1-12
X,P	ROMEIRA B ET AL: "Wireless injection locking and phase noise reduction in a semiconductor laser driven by a resonant tunnelling diode nonlinear oscillator" LASERS AND ELECTRO-OPTICS 2009 AND THE EUROPEAN QUANTUM ELECTRONICS CONFERENCE. CLEO EUROPE - EQEC 2009. EUROPEAN CONFERENCE ON, IEEE, PISCATAWAY, NJ, USA, 14 June 2009 (2009-06-14), page 1, XP031504642 ISBN: 978-1-4244-4079-5 the whole document -----	1-17
X,P	BRUNO ROMEIRA ET AL: "Nonlinear Dynamics of Resonant Tunneling Optoelectronic Circuits for Wireless/Optical Interfaces" IEEE JOURNAL OF QUANTUM ELECTRONICS, IEEE SERVICE CENTER, PISCATAWAY, NJ, USA, vol. 45, no. 11, 1 November 2009 (2009-11-01), pages 1436-1445, XP011279448 ISSN: 0018-9197 the whole document -----	1-17
X,P	ROMEIRA B ET AL: "Synchronizing optical to wireless signals using a resonant tunneling diode laser diode circuit" IEEE LASERS AND ELECTRO-OPTICS SOCIETY, 2008. LEOS 2008. 21ST ANNUAL MEETING OF THE, IEEE, PISCATAWAY, NJ, USA, 9 November 2008 (2008-11-09), pages 145-146, XP031366143 ISBN: 978-1-4244-1931-9 the whole document -----	1-12

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2009/002637

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
WO 0072383	A	30-11-2000	AU	5092500	A	12-12-2000
			CA	2398287	A1	30-11-2000
			EP	1183736	A1	06-03-2002
WO 02088834	A	07-11-2002	AU	2002255127	A1	11-11-2002
			CA	2445566	A1	07-11-2002
			EP	1381909	A2	21-01-2004
			JP	2004524589	T	12-08-2004
			US	2004247218	A1	09-12-2004