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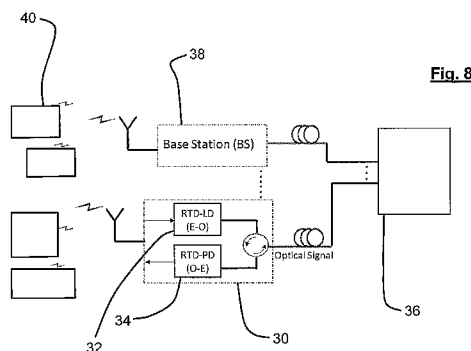
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(54) Title: INTERFACES AND METHOD FOR WIRELESS-OPTICAL AND OPTICAL-WIRELESS CONVERSION



(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.

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

The present invention relates to telecommunications
interfacing systems and methods for interfacing

5 telecommunications signals. The invention has particular
applicability to interfacing wireless signals with optical
signals and/or interfacing optical signals with wireless
signals.

10 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
15 delivering high-bandwidth mobile access. See, for example,
Sauer and Kobayakov 2007 (Sauer, M. and Kobayakov 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
20 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
25 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
5 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.

10 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,
15 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
20 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
25 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
5 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
10 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
15 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
20 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
25 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.

5 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
10 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
15 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
20 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
25 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
5 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
10 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
15 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
20 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
25 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.

5

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
10 synchronisation between the sub carrier signal and the oscillator is used to transfer digital information from the optical domain to the electronic domain.

15 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
20 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
25 phase of a wireless signal can be 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-State circuits 39 1415-1424 2004).

5

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
10 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
15 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-
20 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
25 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.

5

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

- 10 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 or at least 900 MHz. For example, the frequency of the wireless signal may be in the range 900 MHz to 2.5 GHz
- 15 (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
- 20 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
- 25 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
5 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:

10 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.
15 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.

20 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
25 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 (2nd harmonic) and phaselocking by wireless injection for an RTD-LD for use in an embodiment of the present invention.

5 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.

10 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
15 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-
20 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
25 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 increase 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.

5

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

10 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

15 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

20 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

25 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
 5 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:

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

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

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

$$\dot{N} = \frac{I}{qV} - \frac{N}{\tau} - g_0(N - N_0) \frac{S}{1 + \epsilon S} \quad (3)$$

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

$$\frac{S}{P_f} = \frac{\Gamma \tau_p \lambda_0}{\eta h \nu} \quad (5)$$

15

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
 20 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 ($\phi_m = 0$ 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/photronics interface device.

The inventors provide further experimental results on phase-locking and 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
5 fundamental oscillations and the 2nd 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.

10

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
15 frequency was observed in the optical output for injected powers even lower than -40 dBm and with significant noise reduction.

20

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,
25 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.

10 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-

15 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

20 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

25 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.

- 5 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
- 10 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
- 15 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.
- 20 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
- 25 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
5 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
10 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,
15 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
20 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
25 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.

- 5 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
10 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
15 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 optoelectronic integrated RTD-LD circuits are used in a
20 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
25 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

5 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
10 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
15 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
20 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,
5 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.
- 10 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.
- 15 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
20 the optical output device is a semiconductor laser or an optical modulator.
5. A device according to claim 4 wherein the optical
25 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.

5 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
10 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.

15

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.

20 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
25 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
5 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
10 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

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

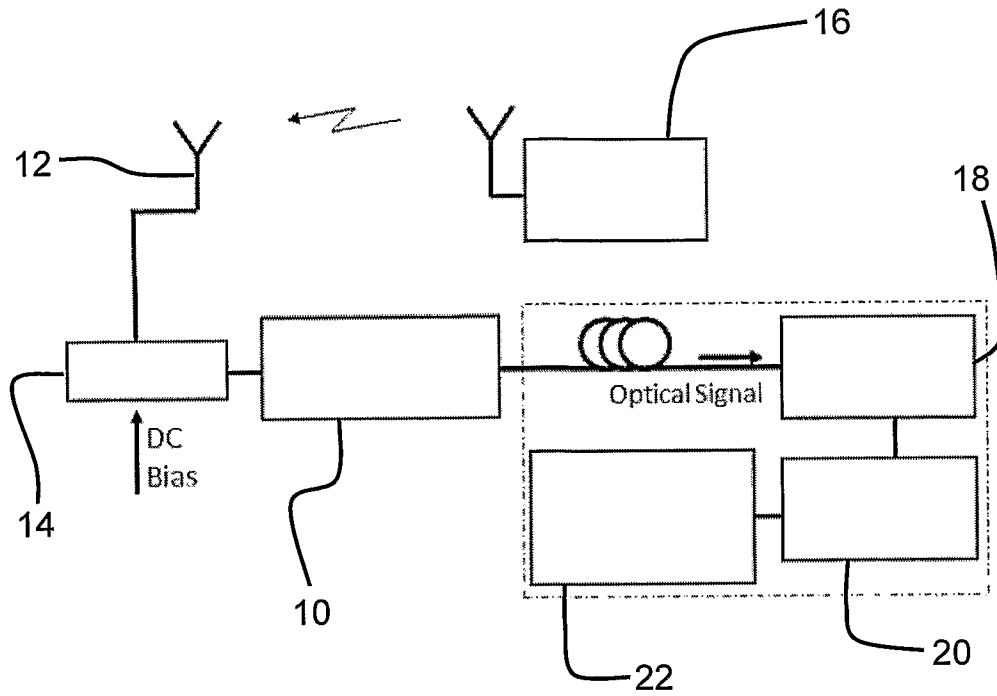
20 16. A method of converting a sub-carrier signal in an optical signal to a corresponding wireless signal via an optical-wireless interface device, the interface device including an optical input and an oscillator synchronised with the sub-carrier signal, the oscillator providing an
25 output to produce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

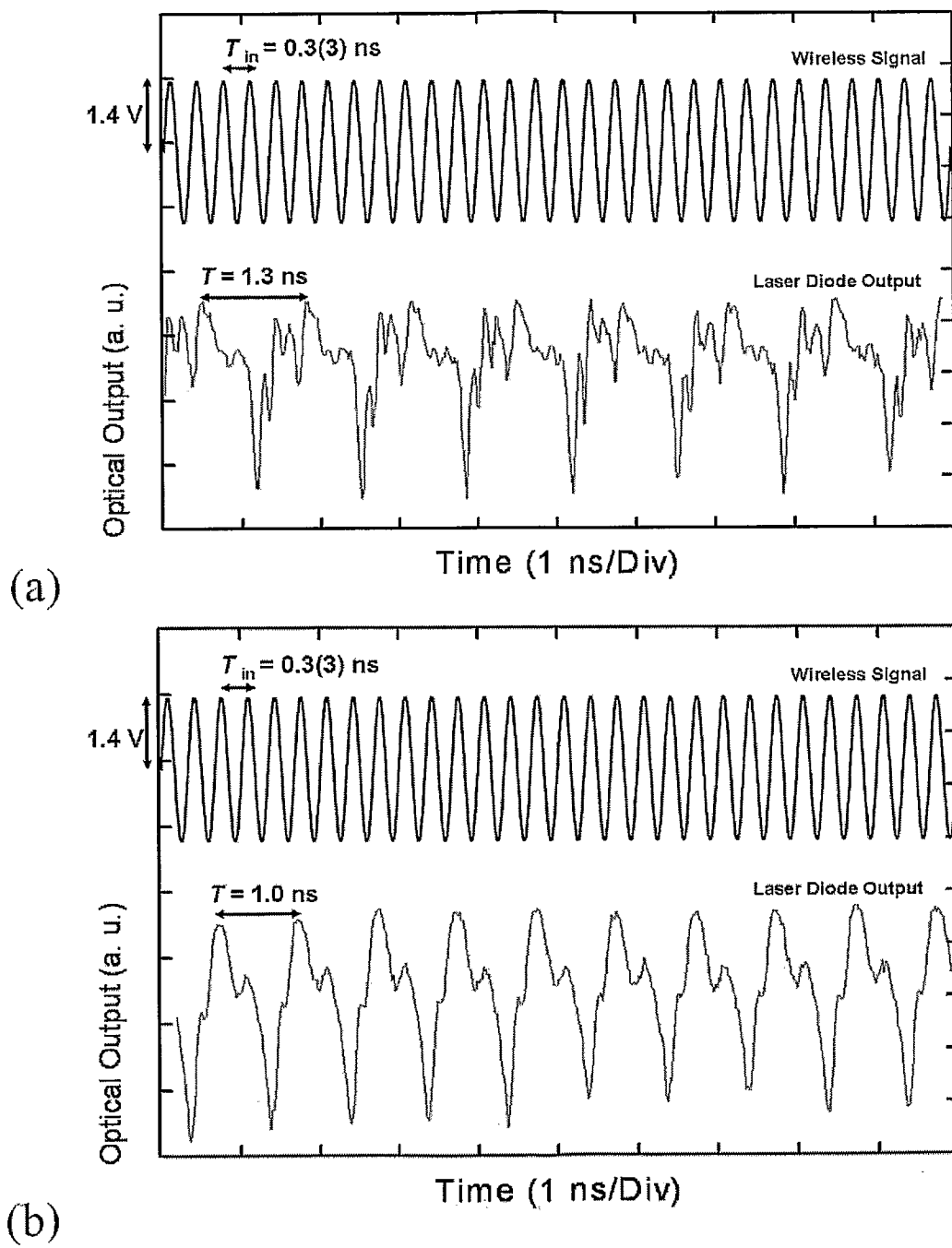
(a) the wireless-optical interface allows conversion of a received wireless signal from a user to a corresponding optical signal for forwarding to the control station, the interface including an oscillator capable of synchronisation with the wireless signal, and an optical output device being controllable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

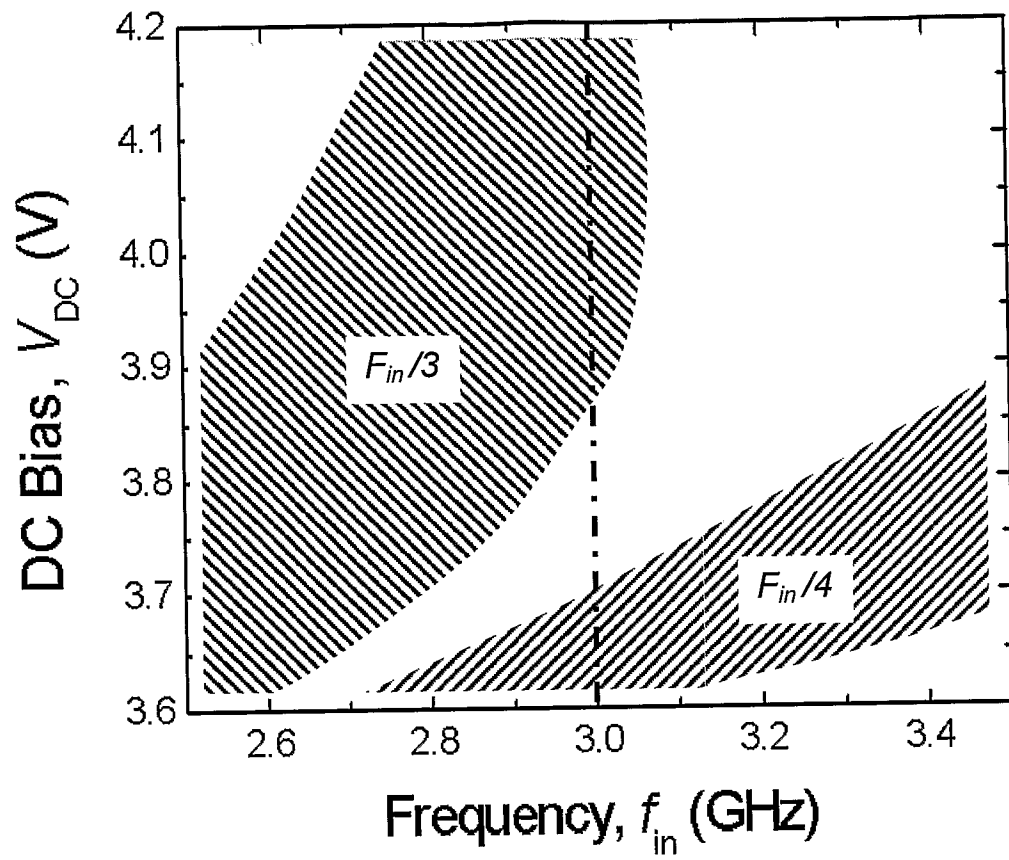
1/8

**Fig. 1**

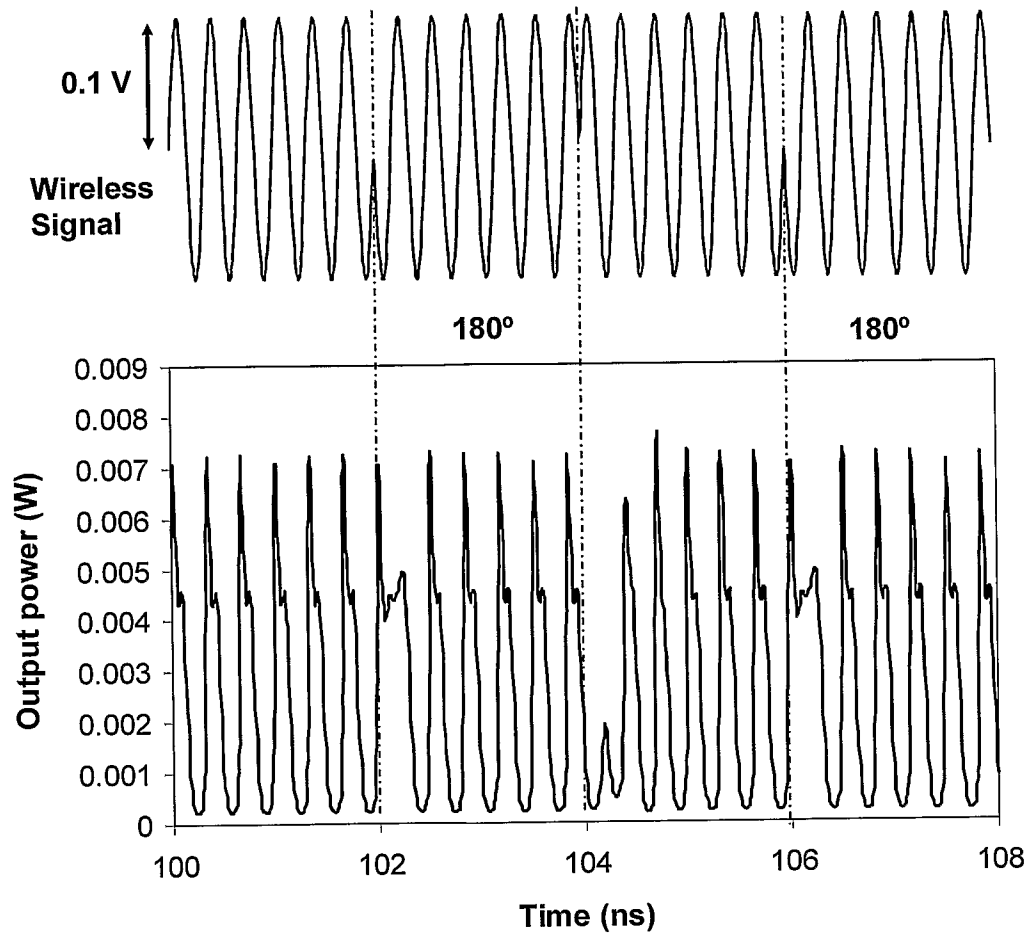
2/8

**Fig. 2**

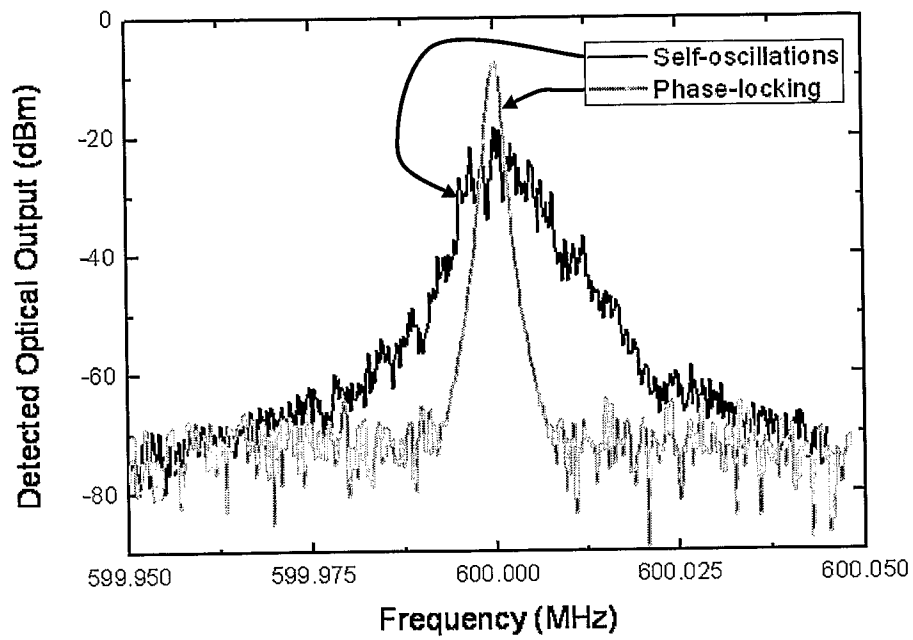
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**Fig. 3**

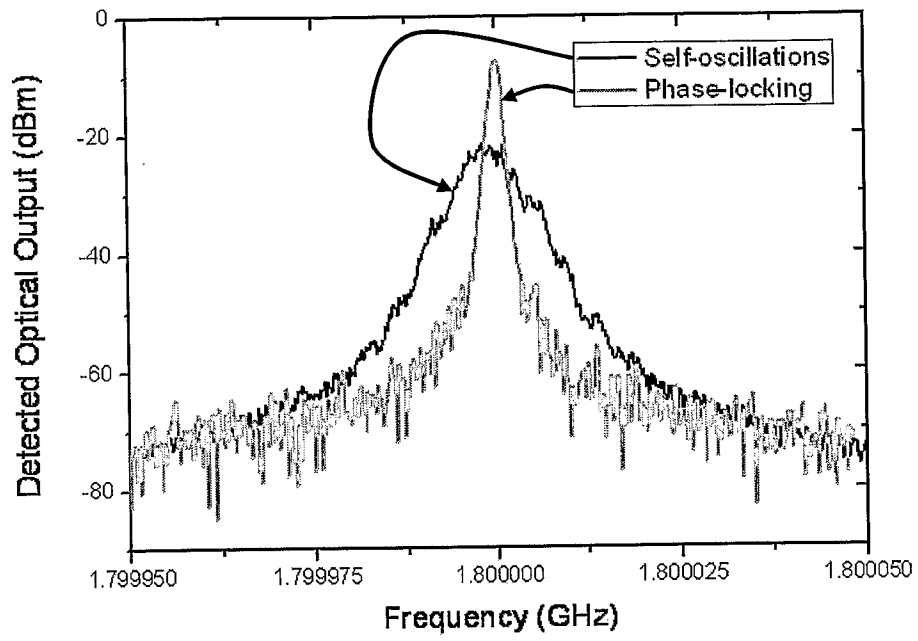
4/8

**Fig. 4**

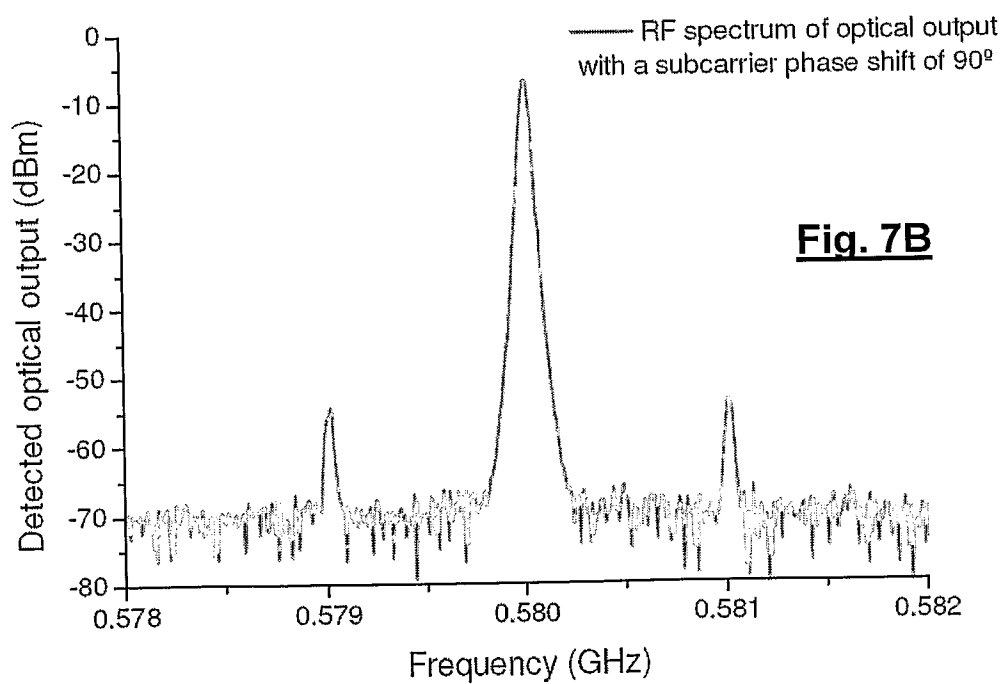
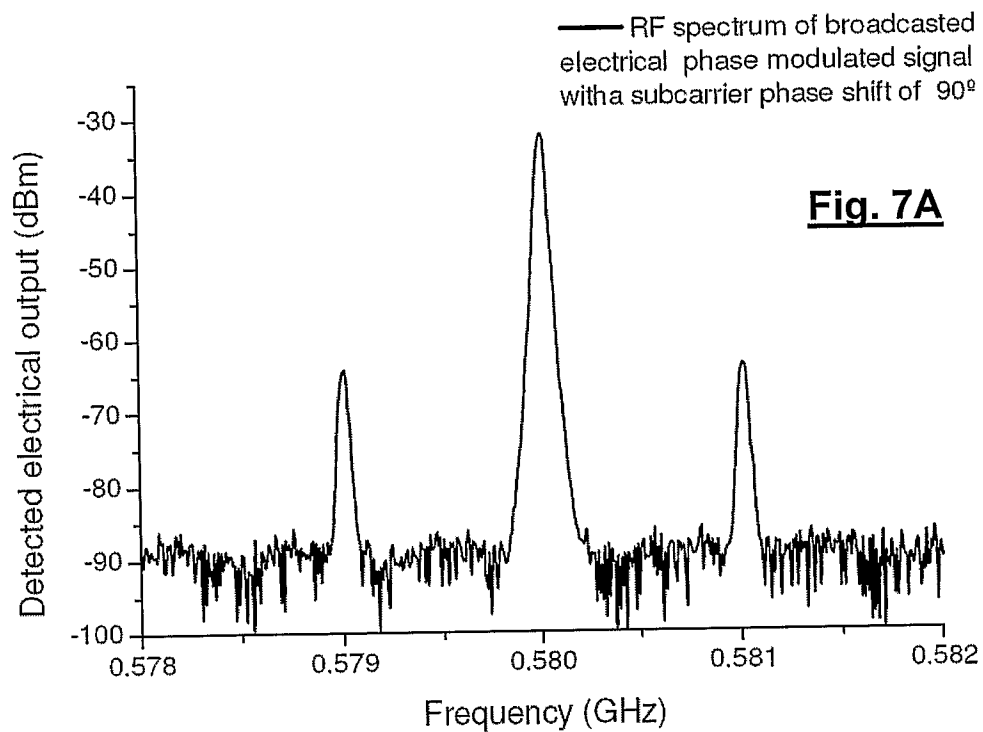
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**Fig. 5**

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**Fig. 6**

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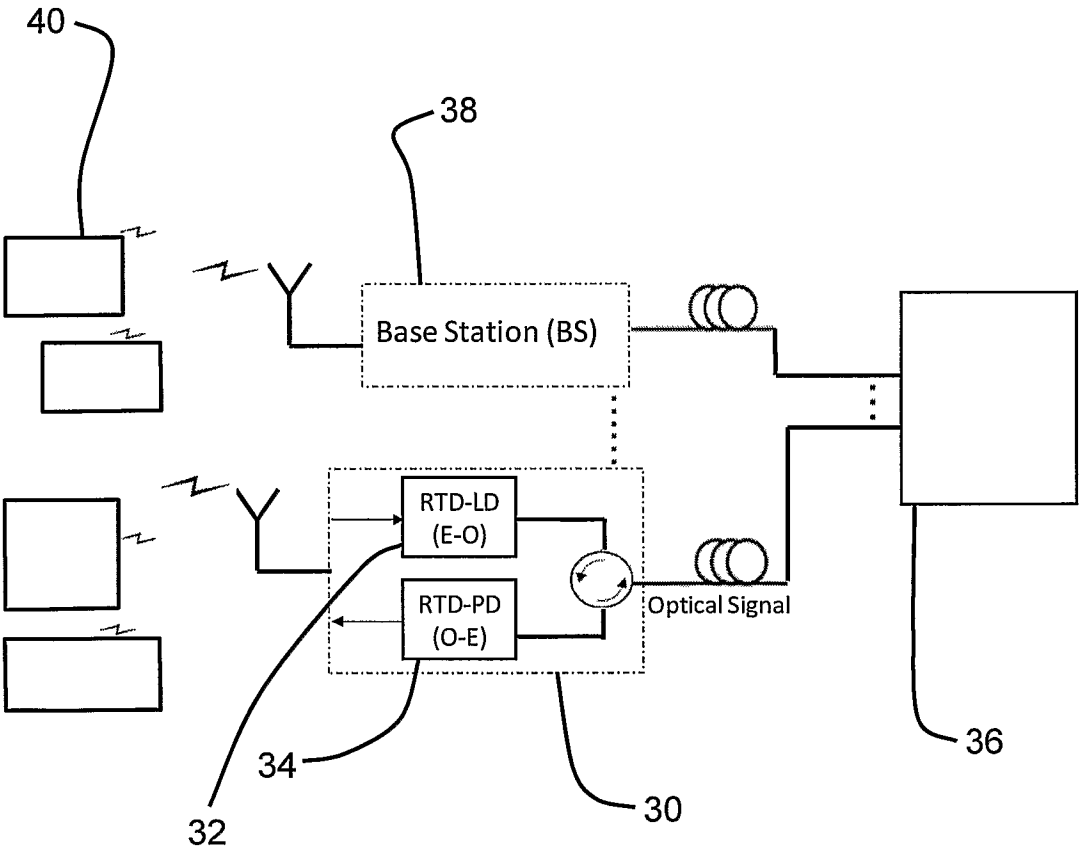


Fig. 8

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

☒ Further documents are listed in the continuation of Box C.☒ See patent family annex.

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- * & * document member of the same patent family

Date of the actual completion of the international search

27 January 2010

Date of mailing of the international search report

03/02/2010

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Authorized officer

Rolan Cisneros, E

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2009/002637

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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International application No

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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Information on patent family members

International application No

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