Optical Generation of Millimeter-Wave Signals for Fiber-Radio Systems Using a Dual-Mode DFB Semiconductor Laser

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***Abstract*— This paper presents a new approach to the optical generation of millimeter-wave signals using a dual-mode multisection distributed feedback semiconductor laser. This simple device is capable of generating high power signals between 40 and 60 GHz with extremely high spectral purity and stability. The two optical modes produced by this laser are heterodyned on an ultrafast photodiode to give a beat signal at the mode difference frequency. The phase noise of the beat signal is greatly reduced by phase-locking the modes using an electrical drive signal applied to the laser at a subharmonic of the beat frequency. Millimeter-wave signals are obtained with a linewidth of less than 10 Hz, a phase noise of less than −85 dBc/Hz at 100 kHz offset, and a locking range of about 500 MHz. Millimeter-wave fiber-radio systems are seen as a major application area for these new compact optical sources.**

I. Introduction

THE USE of millimeter-wave radio for future broadband service provision seems assured since the ability to provide these services with tetherless connectivity—either cordless or mobile—is expected to be in great demand. Broadband services to the home, such as interactive multimedia services (IMS), are already being tried by a number of operators worldwide, including BT in the UK, and millimeter-wave radio is being considered as a supplement to fiber or copper for the final drop to the customer.

The restricted spectrum available at microwave frequencies is a major problem, and therefore new frequency bands situated in the millimeter-wave region between 30–70 GHz have been considered. These frequencies also have other advantages, especially for short-range links. Atmospheric attenuation is high—around 14 dB/km at 60 GHz—which means that frequency channels can be re-used more often, leading to greater spectral efficiency. Furthermore, high antenna gain is more easily achieved at millimeter-wave frequencies, which leads to a reduced transmitter power requirement. These features define the most suitable use for millimeter-wave radio—i.e. for short range, low power links. A further advantage is that this frequency band is currently under-used and regulatory bodies are particularly keen to encourage licensing to fully utilize the spectrum in this band.

Radio over fiber is a very attractive technology for these systems. Here, the millimeter-wave radio signals are placed on an optical carrier and distributed by means of an optical fiber network to points of radiation (antenna sites). The optical fiber network provides high frequency, wideband, low loss, and interference immune signal distribution. Several important advantages accrue from such a technique. The generation of the high frequency signals takes place at a central location, where equipment can be shared between a number of antenna sites, and where it can be protected from attack by sun, wind, and rain. The equipment required at the remote antenna site can now be greatly simplified, leading to small, lightweight, low cost antenna units with low power consumption. These are very important considerations, especially when deploying a large number of units. For these reasons, radio over fiber is likely to be the most cost effective enabling technology for broadband wireless service provision. Fiber-radio systems (systems that use radio over fiber and also incorporate a free-space radio link) are currently under investigation [1]–[3]. A simplified example of a fiber-radio distribution network is shown in Fig. 1.

Millimeter-wave modulation using currently available optical sources is not straightforward. Direct modulation of laser diodes is restricted to a maximum frequency of around 30 GHz, even in the research laboratory. External modulation has been reported up to 75 GHz [4] but most commercially available devices are limited to around 30 GHz and, in general, high insertion loss and high drive voltages limit the usefulness of this approach.

The main techniques that are currently being investigated to overcome these limitations include optical heterodyning [5], [6], harmonic generation [7]–[11], resonant enhancement of semiconductor laser response [12]–[16], and optical injection locking of Fabry Perot laser modes [17], [18]. Optical heterodyning offers the prospect of high power levels, but normally involves two discrete semiconductor lasers and the requirement for relatively complex feedback systems to control the frequency or the phase of the generated signal. Harmonic generation is inefficient since the power is usually distributed over a large number of harmonics and only one harmonic is selected. Resonant enhancement of laser diodes requires a millimeter-wave synthesizer at the frequency of interest, and the devices must be capable of responding to this frequency.

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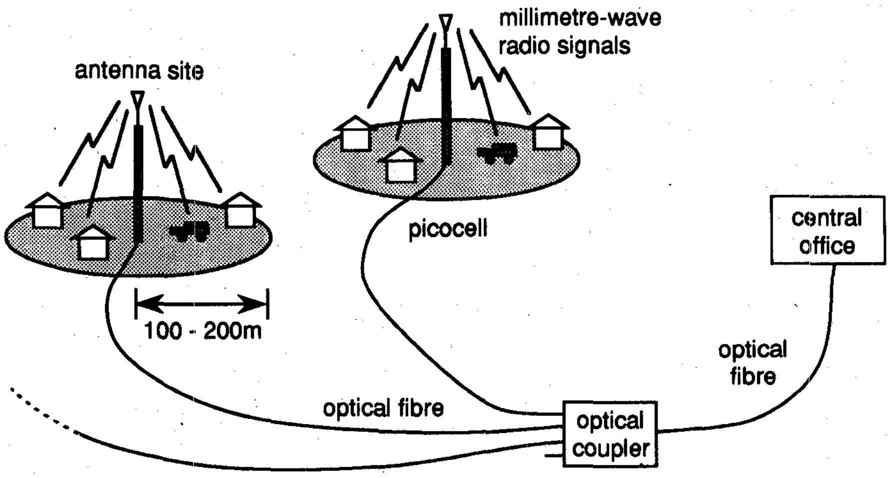

Fig. 1. A simplified example of a fiber-radio distribution network.

Optical injection locking of Fabry Perot laser modes requires master and slave lasers, careful optical alignment, and a very high level of temperature control.

To date, very few optical methods have been reported to generate millimeter-wave signals at around 60 GHz. An optically driven heterojunction bipolar transistor has been used to produce 59.5 and 65.12 GHz millimeter-wave signals with 3 dB linewidth of 2.5 MHz (driven by heterodyned optical sources) and 500 kHz (driven by a mode-locked laser) [19]. A dual-mode optical source has been developed by the consortium of the European project RACE—Microwave Optical Duplex Antenna Link (MODAL) [20]–[23]. This technique is based on double sideband modulation with suppressed carrier, and uses an electrooptic modulator overdriven by a subharmonic of the desired signal to obtain frequency doubling or quadrupling. A 60 GHz signal is generated with a 3 dB linewidth of 30 Hz (limited by the resolution of the spectrum analyser) and with phase noise of about −40 dBc/Hz close to the carrier [23]. However, the power levels of the signals generated by this technique are very low, and an optical amplifier is required to raise the signal to an acceptable level.

In this paper we present the development and the use of a new semiconductor laser optical source for the generation of pure millimeter-wave signals between 40–60 GHz. The device is a single chip dual-mode multisection long-cavity distributed feedback semiconductor laser (DFB), developed at BT Laboratories [24]. The two optical modes produced at the output of the device have a frequency separation equal to the desired millimeter-wave signal. A beat signal is obtained by optically heterodyning the two modes on a wideband p-i-n photodiode.

Phase locking of the millimeter-wave beat signal (to suppress beat phase noise) is obtained by applying a drive signal to one of the laser sections at a subharmonic of the desired signal. In contrast to previous techniques used to obtain millimeter-wave signals by optical methods, this is a straightforward way of obtaining pure millimeter-waves using a single semiconductor laser chip [25]. This method is capable of producing the high power expected from the optical mixing process without the complex feedback control usually associated with this technique. This advantage is due in part to the optical modes that are required for mixing having originated in a single cavity.

This paper is structured as follows. In Section II we describe the dual-mode DFB semiconductor laser; the design, the fabrication and the device characteristics. Section III presents measurements of the millimeter-wave beat signal between the two optical modes. Section IV describes experiments carried out with phase locking to obtain very narrow linewidth millimeter-wave signals using electrical subharmonic drive. Finally, in Section V, we discuss the main implications of the results obtained, suggesting new steps to produce an improved dual-mode single chip semiconductor laser optical source.

II. Dual-Mode DFB Semiconductor Laser

A. Device Design and Fabrication

The laser is a specially modified distributed feedback semiconductor laser (DFB) in which oscillation occurs simultaneously on both sides of the Bragg frequency [24]. The mode separation is adjusted to the desired value by reducing the grating strength coefficient, κ. In this case, the usual efforts to lift the DFB laser degeneracy have not been taken. The grating strength coefficient is the major parameter governing the mode separation in a dual-mode DFB laser. Design data were obtained using the relation below, based on the expression for the FWHM bandwidth of a grating filter [26]

$$\Delta f \approx \frac{1.5\sqrt{2}c\kappa}{\pi n_e \tanh(\kappa L)}$$

where Δf is the mode frequency separation, L is the device length, and n_e is the effective refractive index without the grating. The additional factor of 1.5 is required to convert the FWHM bandwidth into the required mode frequency separation. A κ value of 9 cm^{-1} was chosen to give the required mode separation of around 60 GHz for a 2-mm-long device. Buried heterostructure lasers were fabricated to this specification with a multisection top electrode configuration. Second-order gratings were fabricated using direct-write

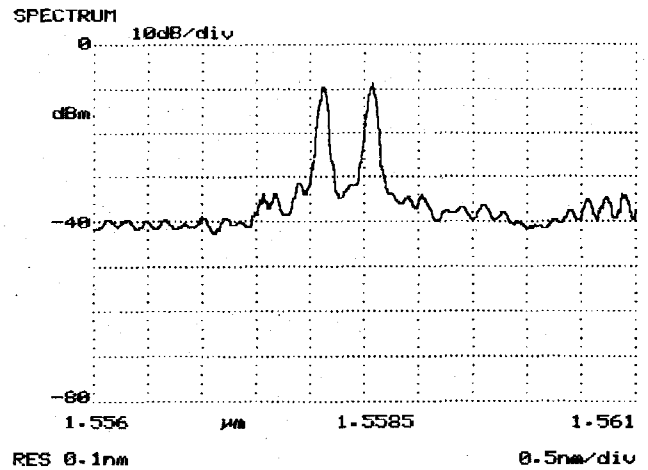

Fig. 2. Typical dual-mode optical spectrum showing a frequency separation of about 60 GHz (0.48 nm).

electron-beam lithography. The laser used here is a DFB device divided into four sections and operates at a wavelength around 1560 nm. The four sections are of length 85, 610, 610, and 730 μm, respectively, with the shortest section at the rear facet. Anti-reflection (AR) coatings were applied to the laser facets, with a residual reflectivity of around 0.1%.

B. Device Characteristics

The laser was mounted on a specially designed submount with four tabs for independent bias of each section. The four sections of the laser were biased at currents of between 20–110 mA each. The optical output from the device, via a lens-ended fiber and an optical isolator, was observed on an optical spectrum analyser (Anritsu MS9003A). The output power of the device under typical operating conditions was around 1 mW (measured in fiber). Fig. 2 shows a typical spectrum where two-moded behavior is produced. In this case the modes have a frequency separation of about 60 GHz (0.48 nm) and all other modes are suppressed by more than 20 dB. This mode spacing is close to the design value. However, similar optical spectra were also obtained with a frequency separation of around 40 GHz (0.32 nm) with different bias currents. At this stage, we are not clear why we can generate two-mode behavior with a range of mode spacings. A thorough evaluation of the two-moded operating region as a function of bias currents has not been undertaken. However, this dual-mode region was reasonably large, and insensitive to small changes in any of the bias currents. Outside this two-moded region, the device exhibited good single-mode behavior.

III. Millimeter-Wave Beat Signal

The optical output was coupled into a wideband InGaAs edge-coupled p-i-n photodiode made at BT Labs [27], with a dc responsivity of 0.27 A/W and a response of −10 dB relative to dc at 60 GHz. The beat signal was displayed by an electrical spectrum analyser (HP 8566B) used with an external preselected mixer (HP11974U) to extend the measurement range to the 40–60 GHz band.

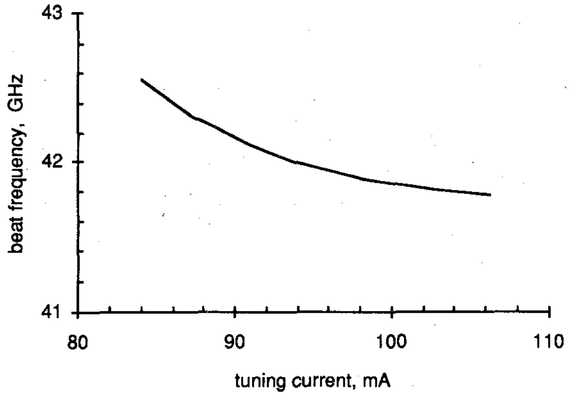

Fig. 3. Beat frequency against bias current for single contact tuning.

A millimeter-wave beat signal was observed with a frequency of 57 GHz, corresponding to the optical mode separation shown in Fig. 2. The beat signal presents a broad (3 dB) linewidth of about 120 MHz since the phase noise of the optical modes is not correlated. A long term frequency drift of 150 MHz was measured for the beat signal. The broad linewidth and instability of this signal means that accurate power measurements were not possible using a spectrum analyser. Power measurements taken using a broadband power sensor (50 MHz–50 GHz) indicate that the modulation depth of the beat signal approaches 100%, i.e., maximum beat power is achieved from the heterodyne process (see next section).

The tuning range of the beat frequency is an important parameter, since there is likely to be a significant difference between the device beat frequency and the desired operating frequency in practice because of processing limitations. Fig. 3 shows the variation of the beat frequency when the mode separation was set to 42 GHz, as a function of the bias current applied to the front section, when the currents in the other sections are maintained at a constant level. From this figure it can be seen that the beat frequency could be tuned over a range of about 1 GHz by changing the bias current. Similar characteristics were observed for tuning the other sections.

IV. Phase Locking Experiments

Phase-locking the two optical modes produced by the laser (to reduce phase noise in the beat signal) was attempted using electrical subharmonic injection. This locking process can be interpreted as being a result of sideband generation for each optical mode at harmonics of the drive frequency. When one of the sidebands from one mode overlaps the second mode, it then provides an injection-locking signal to that mode. The same also happens with the other mode so that each mode is injection-locked by a sideband of the other. Therefore, when the modulation frequency is applied at a subharmonic of the beat signal, it is possible to obtain enhancement and locking of the beat signal with most of the beat power transferred to this locked signal. To attempt this locking process, a drive signal at a subharmonic of the beat signal frequency was applied to the short section of the laser diode. This microwave power was supplied via a bias tee using a synthesized oscillator (HP 8341B) connected to a broadband

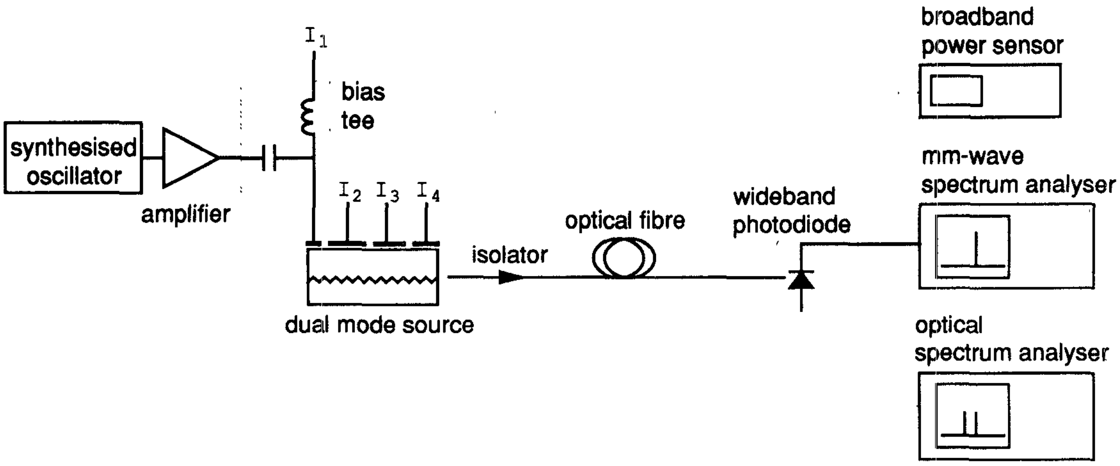

Fig. 4. Experimental arrangement for phase-locking measurements.

power amplifier (HP8349B). This amplifier allowed power up to around 27 dBm to be provided over a broad range of frequencies. No impedance matching was used. Fig. 4 shows this experimental arrangement.

Experiments were performed for two distinct beat frequencies (42 and 57 GHz), obtained at different bias current settings. For the experiments at 57 GHz, most of the data was obtained using the 9th subharmonic, at a drive frequency of around 6.3 GHz. This subharmonic was chosen because of the modulation frequency limit imposed by the laser mounting parasitics. The experiments at 42 GHz used a drive frequency of 5.3 GHz (8th subharmonic). Similar results could be obtained by using other harmonics at both beat frequency settings.

Fig. 5 shows a sequence of spectrum analyser traces obtained as the drive frequency was varied so that its 9th harmonic was moved around the beat signal resonance peak at 57 GHz. The drive power was kept constant at 15 dBm. Here, the effects of phase-locking are clearly seen. As the drive frequency is changed, the beat frequency is pulled to the harmonic frequency and the power in the beat signal is transferred to the harmonic, enhancing the power in the harmonic by at least 20 dB. This situation is maintained over a range (the locking range) of about 500 MHz, after which the beat signal power is partially restored and the power in the harmonic is reduced by 3 dB. This mechanism is similar to that seen for mode-locked semiconductor lasers.

Fig. 6 is a close-up of the 57 GHz phase-locked signal. In this case we used an optical amplifier with low gain (around 4–5 dB) to lift the signal from the analyser noise floor sufficiently to see the signal phase noise. The phase noise is −77 dBc/Hz at 10 kHz offset, and less than −85 dBc/Hz at 100 kHz offset. We believe that this noise floor may be attributed to the drive oscillator phase noise degraded by the harmonic number (the phase noise of the drive oscillator is −86 dBc/Hz at 10 kHz offset). The 3 dB linewidth of this signal was less than 10 Hz (limited by the spectrum analyser resolution bandwidth). Initial investigations show that the purity of these signals is not degraded by transmission over 25 km of optical fiber. The power level of this signal without optical amplification was −50 dBm.

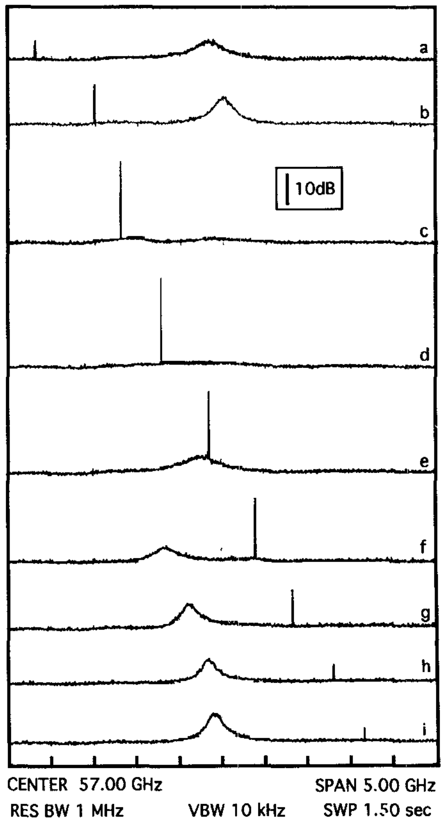

Fig. 5. Sequence of spectrum analyser traces produced by varying the drive signal frequency so that its 9th harmonic crosses the beat signal (around 57 GHz). Drive power was kept constant at 15 dBm.

Other harmonics of the drive signal were also obtained. Fig. 7 shows the harmonics in the 40–60 GHz band, and also lower frequency harmonics measured without the external mixer. The power in each harmonic has been corrected for the relative response of the photodiode and the mixer. In this experiment, the drive power was set to 21 dBm. The enhancement of the harmonic (9th) at the mode beat frequency can be seen clearly from this figure, where a power level ten times that of its is nearest neighbours is observed. Also evident from this figure is the high power in the fundamental

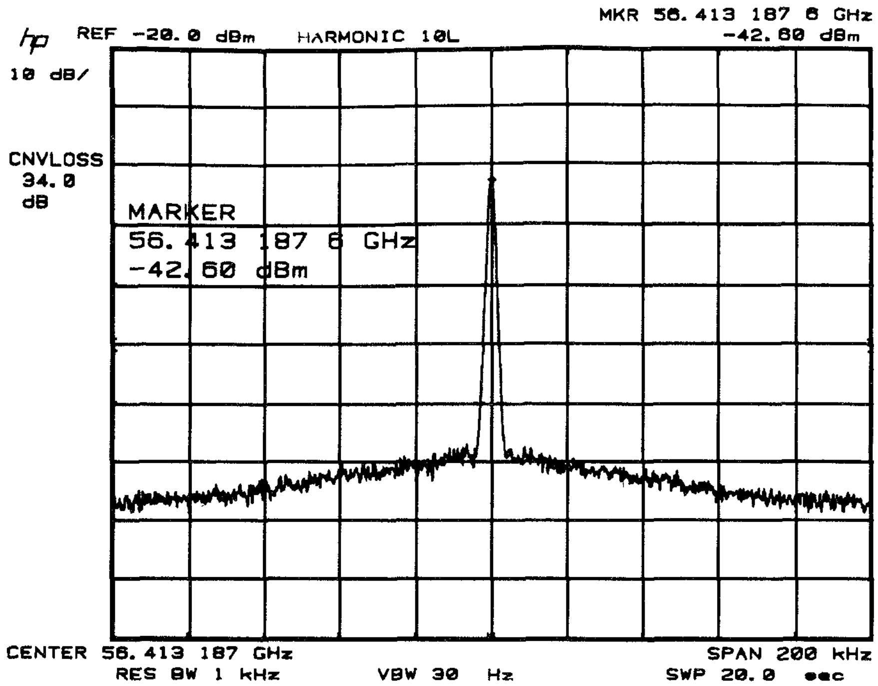

Fig. 6. Phase locked signal at 57 GHz (close-up of Fig. 5, trace d). 10 dB/div vertical, Res BW = 1 kHz, span = 200 kHz.

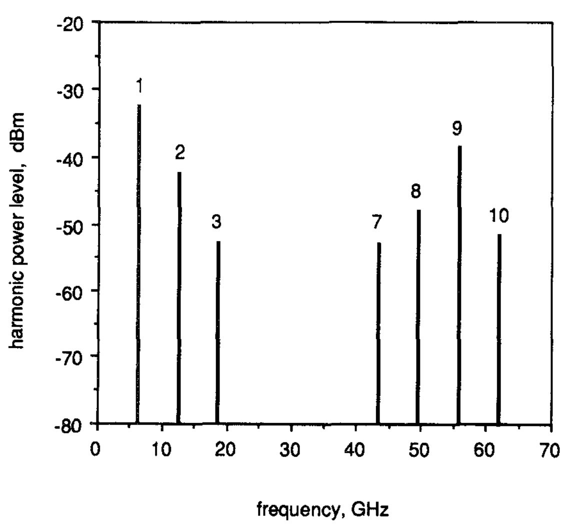

Fig. 7. Power level as a function of frequency for harmonics of drive signal, with beat signal at 57 GHz. The frequency and power of the drive signal were 6.2 GHz and 21 dBm, respectively.

of the drive signal, which limits the modulation depth of the enhanced 9th harmonic to around 10–20%.

In order to measure the modulation depth of the phase-locked signal, experiments were conducted with the beat frequency set to around 42 GHz. At this frequency, similar phase-locked signals could be produced to those described earlier at 57 GHz. For example, a 42 GHz signal was obtained with a phase noise of less than −80 dBc/Hz at 10 kHz offset and a power level of −40.1 dBm and is shown in Fig. 8. The total signal power was measured using a broadband power sensor, and a value of −32.3 dBm was obtained. We calculate the modulation depth of the phase-locked signal to be around 16%, based on these values.

The locking range of this signal was also investigated under these conditions. In this case, the modulation frequency was varied as the drive signal power was kept constant. At each drive frequency, the power and frequency of the locked signal was noted. A (3 dB) locking bandwidth of more than 400 MHz was obtained.

V. Discussion and Conclusion

In this paper we have presented initial investigations of a useful semiconductor laser device that is capable of generating high power millimeter-wave signals with very low phase noise and high stability. A single chip multicontact DFB semiconductor laser was designed to produce a dual optical mode output. These modes beat in a wideband photodiode to generate the desired millimeter-wave beat signal at a frequency equal to the separation of the two optical modes. This signal can be set to a range of frequencies in the range 40–60 GHz by appropriate control of individual contact bias currents, and at each of these frequencies, single contact current tuning gives a range of around 1 GHz. The beat signal was locked in phase by driving the laser at a subharmonic of the beat signal frequency. The phase noise of a 57 GHz signal was less than −85 dBc/Hz at a frequency offset of 100 kHz, and the locking range was around 500 MHz.

We have interpreted the data presented in this paper in terms of phase-locking. This interpretation comes as a result of Fig. 5, where a clear transfer of power between noise and signal takes place as one is swept across the other. Classic phase-locking behavior, such as insensitivity of signal power to drive power after locking, is not observed, however. We believe that classic phase-locking behavior is being masked because of the high drive power levels required, which is a consequence of the subharmonic nature of the drive signal.

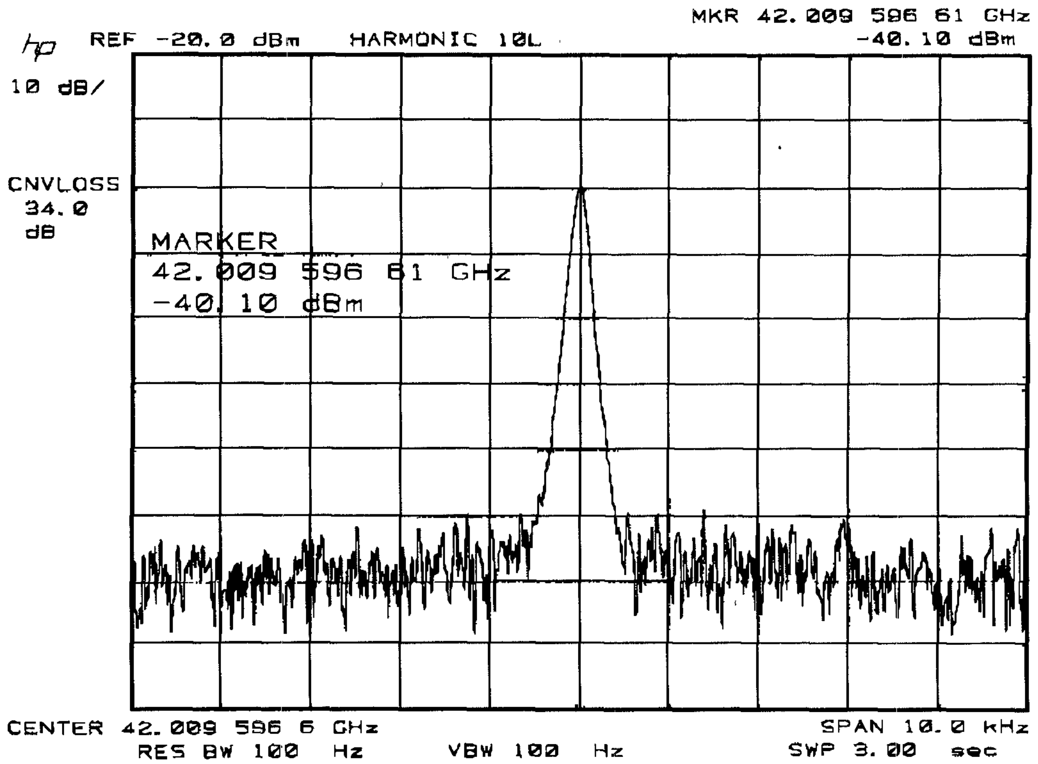

Fig. 8. Phase-locked signal at 42 GHz. (10 dB/div vertical, Res BW = 100 Hz, span = 10 kHz).

A high drive power upsets the static conditions in the laser, which were originally set up to produce a simple two-moded output with equal power in each mode. The modulating current disturbs this ideal condition. As the drive power is varied, therefore, the laser moves away from the conditions set for optimum beat power.

The results obtained here provide useful information for new laser designs for devices with a more controllable optical spectrum. A shorter structure with fewer contacts should be simpler to use and give more straightforward behavior, although this design is likely to involve a more complex grating structure since the uniform grating design adopted for this work requires long devices with weak gratings.

The modulation depth of the phase-locked signals measured in this work is less than 100%, which is caused by the high power produced at the output at the fundamental drive frequency. This is an unavoidable consequence of using a subharmonic injection-locking technique as opposed to fundamental injection-locking. However, the advantages of using a subharmonic to lock the millimeter-wave signal (low frequency oscillator can be used and greatly relaxed high frequency device packaging) more than compensates for this penalty. Although the absolute power in our millimeter-wave signals is high, modulation depth can be important in practical systems where optical power amplification is used. In this case, a signal with low modulation depth would quickly lead to saturation in the amplifier. Improved laser packaging is expected to allow higher frequency drive signals to be used, and thus a lower harmonic number. In turn, this would allow locking to take place at lower drive power levels, which would lead to higher modulation depth.

The absolute power levels of our phase-locked signals is in the range −40 to −50 dBm, without correction for photodiode response and without any optical amplification. As far as we know, these are the highest power levels achieved for optically generated signals in this frequency range without amplification.

In conclusion, we have developed a new, compact, simple, and tuneable optical source of pure, high power millimeter-wave signals. This is the first time that optical generation of millimeter-wave signals has been obtained with high purity and high power without amplification. Initial investigations show that the purity of these signals is not degraded by transmission over 25 km of optical fiber. This is a major step forward in the development of enabling technology for millimeter-wave broadband wireless systems over optical fiber networks.

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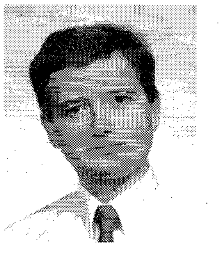

David Wake was born in Sunderland, England, in 1956. In 1979 he graduated from U.W.I.S.T., Cardiff, with a B.Sc. degree in applied physics. In 1987, he was awarded a Ph.D. degree from the University of Surrey, Guildford, for his work on the development of OEIC's for low noise optical receivers.

In 1979 he joined BT Labs, where he worked on the development of a range of semiconductor optoelectronic devices based on the InGaAsP/InP alloy system for optical communications. Since 1987, his work has mainly involved high speed optoelectronics for millimeter-wave fiber-radio systems. He currently leads a team concerned with research into devices and subsystems for fiber-fed radio.

Claudio R. Lima (S'94) was born in Maceio, Brazil, on May 25, 1964. He received the B.Sc. from University of Paraiba-UFPb, Campina Grande, Brazil, and the M.Sc. from University of Campinas-UNICAMP, Sao Paulo, Brazil, in 1987 and 1991, respectively, both in electrical engineering. In 1986 he was involved in the design and development of a miniaturized, tunable and high power CO_2 laser at the Laser Division of the Aerospacial Technological Center-CTA-IEAv, Sao Jose dos Campos, Brazil. His Master's thesis involved the design and construction of tunable external cavity semiconductor lasers for coherent optical communications.

Currently, he is working towards a Ph.D. degree in electronic engineering at the Optical Communications Research Group of the University of Kent at Canterbury, UK. Since 1991 he has been engaged in research on optical generation of microwave and millimeter-wave signals using gain-switched and mode-locked semiconductor lasers. More recently he has been involved in research on optical millimeter-wave interfaces for fiber-radio systems with BT Laboratories. His current research interests include microwave and millimeter-wave optoelectronics, high-speed semiconductor lasers, mode-locked and gain-switched semiconductor lasers, and millimeter-wave fiber-radio systems.

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