

Multifunctional Fiber-Optic Microwave Links Based on Remote Heterodyne Detection

Ulrik Gliese, Torben Nørskov Nielsen, Søren Nørskov, and K. E. Stubkjær, *Member, IEEE*

Abstract—The multifunctionality of microwave links based on remote heterodyne detection (RHD) of signals from a dual-frequency laser transmitter is discussed and experimentally demonstrated in this paper. Typically, direct detection (DD) in conjunction with optical intensity modulation is used to implement fiber-optic microwave links. The resulting links are inherently transparent. As opposed to DD links, RHD links can perform radio-system functionalities such as modulation and frequency conversion in addition to transparency. All of these three functionalities are presented and experimentally demonstrated with an RHD link based on a dual-frequency laser transmitter with two offset phase-locked semiconductor lasers. In the modulating link, a 1-Gb/s baseband signal is QPSK modulated onto a 9-GHz RF carrier. The frequency converting link demonstrates up-conversion of a 100-Mb/s PSK signal from a 2-GHz carrier to a 9-GHz carrier with penalty-free transmission over 25 km of optical fiber. Finally, the transparent link transmits a standard FM video 7.6-GHz radio-link signal over 25 km of optical fiber without measurable distortion.

Index Terms—Microwave communication, millimeter-wave communication, optical-fiber communication, optical phase-locked loops, semiconductor lasers, signal processing.

I. INTRODUCTION

THE interest in fiber-optic micro- and millimeter-wave (MW) links has been steadily increasing and the proposed applications are manifold ranging from delay lines over phased-array antenna feeders to backbone networks for cellular phone systems. The links can be implemented either by the use of direct detection (DD) techniques or remote heterodyne detection (RHD) techniques.¹ Many such links have been proposed, analyzed, and experimented.

In the DD links, the MW signal is intensity modulated (IM) onto the optical carrier from a laser. The optical signal

Manuscript received January 11, 1996; revised October 10, 1996 and February 28, 1997. This work was supported in part by ESA, under ESTEC Contract 110938, Contract 122250, and Contract 134212.

U. Gliese and K. E. Stubkjær are with the Center for Broadband Telecommunications, Department of Electromagnetic Systems, Technical University of Denmark, DK-2800 Lyngby, Denmark.

T. N. Nielsen was with the Center for Broadband Telecommunications, Department of Electromagnetic Systems, Technical University of Denmark, DK-2800 Lyngby, Denmark. He is now with Bell Laboratories, Lucent Technologies, Crawford Hill, NJ 07733 USA.

S. Nørskov was with the Center for Broadband Telecommunications, Department of Electromagnetic Systems, Technical University of Denmark, DK-2800 Lyngby, Denmark. He is now with Nokia Mobile Phones, DK-1790 Copenhagen, Denmark.

Publisher Item Identifier S 0018-9480(98)03155-X.

¹Conventional heterodyne detection proves difficult, unless lasers with very low phase noise are employed.

is then transmitted through the optical fiber, and the MW signal is recovered by DD in a photodiode. In the RHD links, two phase-correlated optical carriers are generated in a dual-frequency laser transmitter with a frequency offset equal to the desired MW frequency. Both optical signals are then transmitted through the optical fiber, and the MW signal is generated by heterodyning of the two optical signals in a photodiode.

Links using IM-DD are inherently signal transparent and, in principle, act as amplifiers/attenuators. Consequently, these links are restricted to MW-signal transport functions. In fact, until now, the fiber-optic technology has primarily been considered for such functions. However, when based on RHD, the technology can offer radio-system functionalities such as modulation and frequency conversion in addition to transparent signal transport. For some applications, this may be of considerable importance.

Naturally, the performance of RHD must be viewed in the light of its higher complexity and cost as compared to IM-DD. The increase in complexity and cost is due to the required dual-frequency laser transmitter. Integration might lead to cost reductions, and transmitter concepts with potential for hybrid and/or monolithic opto-electronic (O/E) integration are, therefore, essential.

In this paper, we present three fiber-optic MW-link experiments demonstrating the feasibility of implementation of the three different radio-system functionalities: modulation, frequency conversion, and transparency. The link used for all three experiments is based on RHD and a semiconductor laser transmitter that has the potential for both hybrid and monolithic O/E-integration.

The paper is organized as follows. The principles and functionalities of RHD are described in Section II, together with different transmitter concepts. Further, the obtainable link functionalities are described in Section III. This is followed by a description in Section IV of the transmitter that is used in the link experiments. After this, the three link experiments and their results are presented and discussed in Sections V–VII. Finally, conclusions are drawn in Section VIII.

II. RHD AND TRANSMITTER CONCEPTS

A. The RHD Principle

The principles of RHD links are quite different from those of IM-DD links. The major difference is that the IM-DD link transmits the MW signal as sidebands on a single laser

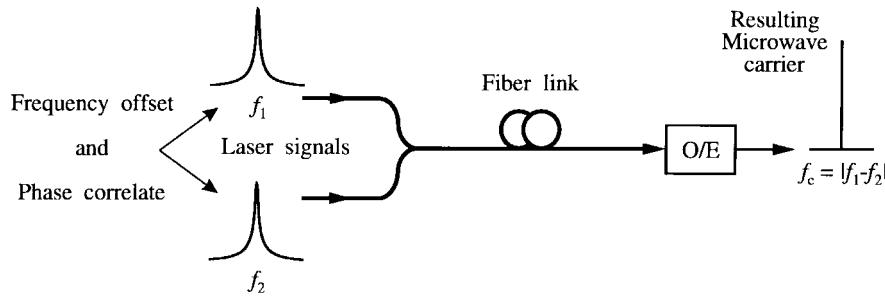


Fig. 1. Principle of RHD fiber-optic MW links.

signal whereas the RHD link generates the MW signal by heterodyning of two laser signals. In this process, the phase noise of the two laser signals transfers directly to the resulting microwave signal. Therefore, it is necessary either to remove the actual laser-signal phase noise or to correlate the phase noise of the two laser signals. Both methods or a combination ideally ensures the generation of a highly phase-stable MW carrier.

A simplified schematic of the RHD principle is shown in Fig. 1. At the transmitter end, two phase-correlated laser signals with a frequency offset of $f_c = |f_1 - f_2|$ are generated by a dual-frequency laser transmitter. Both laser signals are transmitted through the fiber link to the receiver end where heterodyning takes place in an O/E-converter (photodiode). Assuming that the phase correlation between the two laser signals is not altered by the fiber link, the resulting beat signal is a highly phase-stable MW carrier with a frequency of f_c .

However, the phase correlation is altered to some extend by the fiber link which, besides transmission attenuation, may limit the system performance due to dispersion effects and fiber nonlinearities. Both chromatic dispersion and polarization-mode dispersion limit the obtainable transmission-distance times MW-carrier frequency product of the link [1], [2]. Further, at high optical input powers, fiber nonlinearities may cause significant problems. This aspect has to the best of the authors' knowledge never been analyzed for neither IM-DD nor RHD fiber-optic MW links. Such an analysis, however, is outside the scope of this paper.

B. Dual-Frequency Laser Transmitters

No details have been presented in Fig. 1 for the dual-frequency laser transmitter of the link, as it can be implemented in many different ways. The general concept, however, is the same for all transmitter types. A MW carrier is used to control the frequency offset and phase correlation between the two laser signals. Further, information content can be modulated onto the optically generated MW signal by modulating one or both of the two laser signals. A variety of possible transmitter concepts have been proposed and investigated:

- 1) dual-mode lasers where the two optical signals are generated from two different oscillation modes in a master laser [3];

- 2) optical frequency shifting where the two optical signals are generated by:
 - a) splitting a master laser signal in two and frequency shifting one part [4], [5];
 - b) single sideband (SSB) modulation of a master laser signal [6], [7];
 - c) suppressed carrier double sideband (SC-DSB) modulation of a master laser signal [8], [9].
- 3) optical offset injection locking where the two optical signals are generated by injection locking of:
 - a) two slave lasers by a master laser [10];
 - b) one slave laser by a master laser [11].
- 4) optical offset phase locking where the two optical signals are generated by phase locking of a slave laser to a master laser [12]–[15].

III. MULTIPLE-LINK FUNCTIONALITIES

In radio systems, the baseband information signal is normally known as the low-frequency (LF) signal. The LF signal is typically modulated onto a carrier resulting in an intermediate frequency (IF) signal. Finally, the IF signal is frequency up-converted to an RF signal suitable for transmission in the radio channel. The three abbreviations LF, IF, and RF are not used to describe specific frequency ranges, rather they are used to describe different signal stages present in most radio systems. For consistency, this terminology is used throughout this paper. Therefore, any radio-transmission signal at no matter which MW frequency is designated the RF signal.

As the carrier and the modulation of the RF signal can be controlled separately in RHD links, the link can perform three different radio-system functionalities depending on how the transmitter is constructed and operated.

- 1) A modulating link that modulates an LF signal, applied at the input of the link, onto an RF signal, delivered at the output at the link.
- 2) A frequency converting link that up-converts an IF signal, applied at the input of the link, to an RF signal delivered at the output of the link. The reverse action, down-conversion, is also possible.
- 3) A transparent link that transfers an RF signal from the input of the link to the output of the link without alteration.

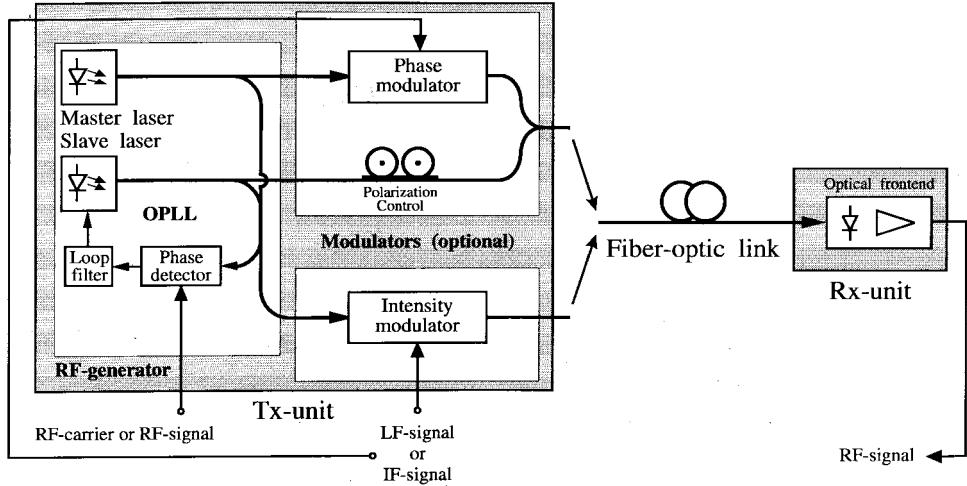


Fig. 2. Principle of the OPLL transmitter.

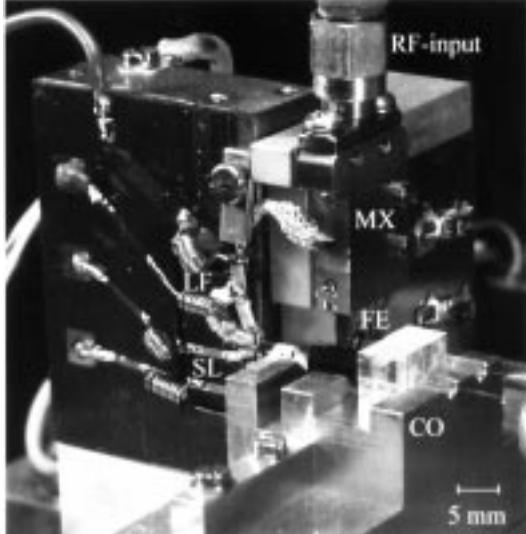


Fig. 3. Photo of the feedback loop of the OPLL RF generator. SL: slave laser. CO: coupling optics. FE: optical frontend. MX: microwave mixer. LF: loop filter.

These three modes of operation are described in detail in Section IV for a transmitter based on optical offset phase locking of two semiconductor distributed feedback (DFB) lasers.

IV. THE OPTICAL PHASE-LOCKED-LOOP LASER TRANSMITTER

A. Setup

As shown in Fig. 2, the dual-frequency laser transmitter consists of an optical phase-locked loop (OPLL) RF generator, [15], and an optical modulator (the possible configurations are described at the end of this section). The OPLL RF generator consists of a free-running master laser with a 2-MHz linewidth, an O/E phase detector (optical frontend and microwave mixer), a loop filter (low-pass with phase-lead correction), and a slave laser with a 6-MHz linewidth [16]. The RF signal generated by the beat of the two semiconductor lasers is, in the phase detector, compared to the RF input signal. The resulting phase

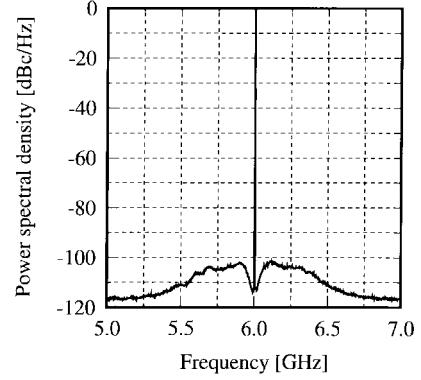


Fig. 4. Power spectral density of the optically generated microwave signal at 6 GHz.

error signal is fed back to the slave laser which is forced to track the master laser. This causes a significant reduction of the phase noise of the beat signal. The OPLL is a second-order loop with a loop feedback bandwidth f_z (as defined in [17]), of 180 MHz, a loop gain of 181 dBHz, and a loop propagation delay τ_d of only 400 ps [15]. A photo of the OPLL feedback loop is shown in Fig. 3 to illustrate how the low-loop propagation delay has been achieved through a very compact setup.

The required feedback bandwidth is independent of the RF signal frequency and only depends on the required RF signal phase noise and the phase noise of the lasers. Therefore, the obtainable RF signal frequency is solely determined by the phase detector RF properties. The OPLL presented here operates a continuous RF range of 3–18 GHz. However, with fast photodiodes and monolithic microwave integrated circuit (MMIC) technology operation in the 60- or 100-GHz frequency bands can be obtained.

B. Performance

The RF signal generated by the OPLL transmitter is shown in Fig. 4 for the frequency of 6 GHz. Close to the carrier, its spectral shape corresponds exactly to that of the injected RF signal. The noise level is as low as -110 dBc/Hz @ 100 kHz of carrier, less than -115 dBc/Hz @ 200 kHz–20 MHz of

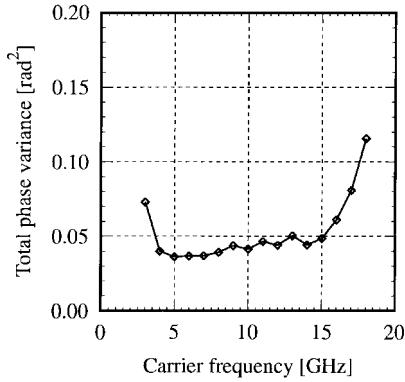


Fig. 5. Total phase variance in a 1-GHz noise bandwidth as a function of the microwave signal frequency.

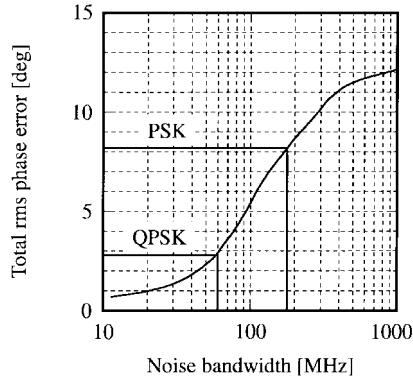


Fig. 6. Total rms phase error for the average 4–15-GHz range performance as a function of the noise bandwidth.

carrier and only -102 dBc/Hz at the offset corresponding to the loop resonance frequency. Of the total signal power, 97.7% is phase locked in the carrier and the total phase variance is as low as 0.04 rad² in a 1-GHz noise bandwidth and only 0.001 rad² in a 50-MHz noise bandwidth.

The total phase variance in a noise bandwidth of 1 GHz is shown as a function of the RF signal carrier frequency in Fig. 5. As seen, the OPLL has an uniform performance in the range of 4–15 GHz with an average phase variance of 0.045 rad². For this value, the total rms phase error is shown as a function of the noise bandwidth in Fig. 6. As shown, QPSK and PSK signals typically require an rms phase error of maximum 2.8° and 8.2° , respectively [2]. For an effective system noise bandwidth of 0.6 times the symbol rate [2], this allows for QPSK operation at bit rates of up to 200 Mb/s, and PSK operation at bit rates of up to 290 Mb/s.

Finally, the locked loop operation is very reliable. An acquisition range of 640 MHz has been measured, and the average time to cycle slip T_{av} is estimated to 10^{11} s. This yields a probability of less than 0.3% for one cycle slip within ten years. To our knowledge, this semiconductor laser OPLL is the best ever reported [15].

C. Configurations

The transmitter described above can be used for any of the three different link functionalities presented in the previous

section. In the following, a description of each of the three functionalities is given in relation to the OPLL transmitter.

- 1) In the modulating link, an unmodulated RF carrier is injected into the phase detector of the OPLL. This ensures phase correlation of the two laser signals at a frequency offset equal to the frequency of the injected RF carrier. Further, one or both of the laser signals are modulated by an LF signal by use of an external optical modulator. The modulation format used for the optical modulation transfers directly to the RF signal generated by RHD at the output of the link. The generated RF signal and, thereby, also its amplitude modulation relates as the square root to the intensity of each laser signal. Therefore, in the case of optical IM, it is necessary to modulate both laser signals with the same LF signal, as shown for the IM configuration of Fig. 2. This ensures a linear amplitude modulation of the RF signal. PM is obtained by modulation of one of the laser signals as shown for the PM configuration of Fig. 2. In this scheme, FM of the master laser cannot be used since it will be tracked by the OPLL.
- 2) In the frequency up-converting link, an unmodulated RF carrier is injected into the phase detector of the OPLL as described above. Further, one or both of the laser signals are modulated by an IF signal or an IF signal set by use of an external optical modulator in either of the same configurations described above. By RHD, the IF signal is frequency up-converted to an RF signal. For the IM method, the linearity only depends on the linearity of the modulator. In contrast, the use of PM for subcarrier modulation inherently results in some signal distortion because it is a nonlinear modulation process [18]. The modulation depth must, therefore, be adjusted depending on the number of IF signals that are to be handled in one signal set [18], [19].
- 3) In the transparent mode, a modulated RF signal is injected into the phase detector of the OPLL. The two lasers are then forced to offset phase lock in such a manner that the optically generated RF signal equals the injected RF signal. After RHD at the receiver, the signal has been transferred directly to the output of the link. With the OPLL, this mode of operation only works for RF signals modulated in either frequency or continuous phase and within the modulation-bandwidth limitations of the loop. In this scheme, an external optical modulator is not present in the setup of Fig. 2.

Proof of concept link experiments have been carried out for each of the three functionalities to demonstrate their feasibility. All of the link experiments are based on the OPLL dual-frequency laser transmitter operating in the wavelength regime of 1550 nm, a conventional optical frontend receiver and standard single-mode fiber. For the distances (0–25 km) and MW frequencies (7–9 GHz) of the link experiments presented in this paper, no limitations occur due to fiber dispersion [1], [2]. This is also verified by the experimental results. The optical power levels in the transmitter were optimized for optimum OPLL performance rather than for maximum

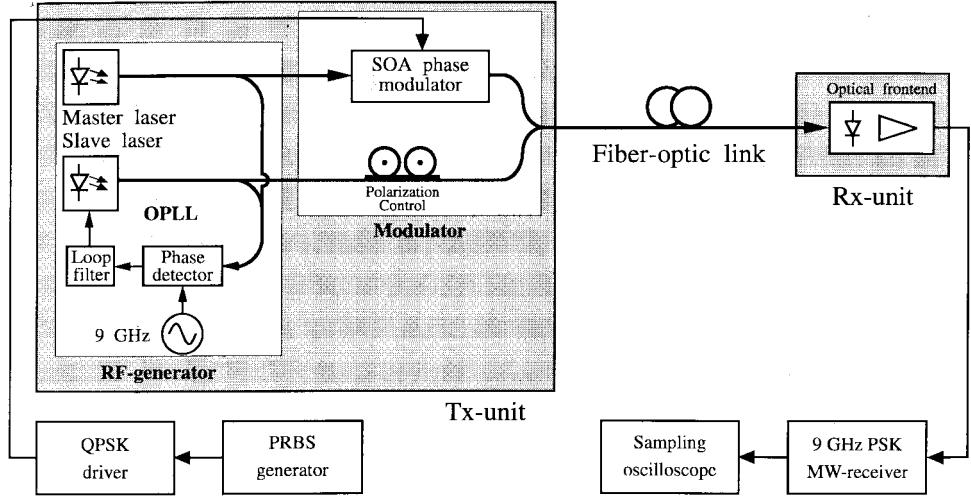


Fig. 7. Configuration of the modulating link.

transmission power. Consequently, each of the two lasers only put approximately -15 dBm into the transmission fiber. At this power level, fiber nonlinearities should have no effect on the link performances.

V. THE MODULATING LINK

A. Experimental Setup

This experiment demonstrates QPSK modulation of an LF input signal with a bit rate of up to 1 Gb/s onto a 9-GHz RF carrier [20]. The experimental setup is shown in Fig. 7. It consists of a pseudorandom bit sequence (PRBS) generator, a QPSK driver/encoder [21], an O/E transmitter (Tx) unit, a fiber-optic link (here only a few meters), an O/E receiver (Rx) unit, a PSK microwave receiver, and a sampling oscilloscope. A DC-12-GHz optical frontend (HP 11982A) is used for the Rx unit. The Tx unit consists of the semiconductor laser OPLL RF generator described in Section IV and an external two-electrode semiconductor optical amplifier (SOA) phase modulator [22], [23].

A four-level LF signal from the QPSK driver/encoder is applied to the SOA phase modulator. This signal QPSK modulates the master laser signal. The two laser signals are transmitted through the fiber to the Rx unit where a QPSK modulated RF signal is generated by RHD. The carrier frequency is determined by the frequency offset between the two lasers in the OPLL, which is chosen to 9 GHz. The resulting modulation on the RF signal is exactly the same as that applied to the optical signal.

B. Modulating Performance

The LF-to-RF modulating link functionality has been verified by analysis of the received RF signal and the demodulated I and Q components. The signal at the output of the Rx unit is shown in Fig. 8. The smooth curve represents the ideal envelope for the QPSK RF spectrum. The measured spectrum is (as seen) very close to the ideal. The imperfect suppression of the carrier (20.5 dB) as well as the spikes

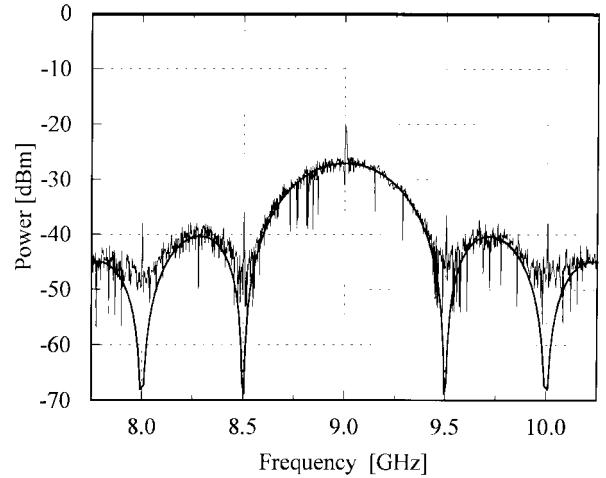


Fig. 8. Power spectrum of optically generated 1-Gb/s QPSK modulated 9-GHz carrier.

between each sidelobe are due to a nonlinear PM response of the SOA phase modulator. This gives rise to a penalty of approximately 1 dB, which is low compared to the 14.5-dB gain of the SOA. The demodulated I and Q components of the 1-Gb/s QPSK signal are shown in Fig. 9. They have been measured with the sampling scope in averaging mode to clear the measurement from phase noise. From the well-defined upper and lower levels of the demodulated signals, it is seen that the SOA modulator both provides the sufficient PM index and has adequate phase linearity to yield a nearly constant amplitude of the signal levels. The residual gain variation of the SOA is also included in the Fig. 9 and is only 1 dB.

C. Link Performance

As shown in Section IV, the OPLL RF generator allows for QPSK transmission of up to 200 Mb/s (60-MHz noise bandwidth). Such a transmission has been carried out using an available PSK receiver with a noise bandwidth of 120 MHz. As expected, this noise bandwidth is too wide, and this is clearly evident from the eye diagram shown in Fig. 10. However,

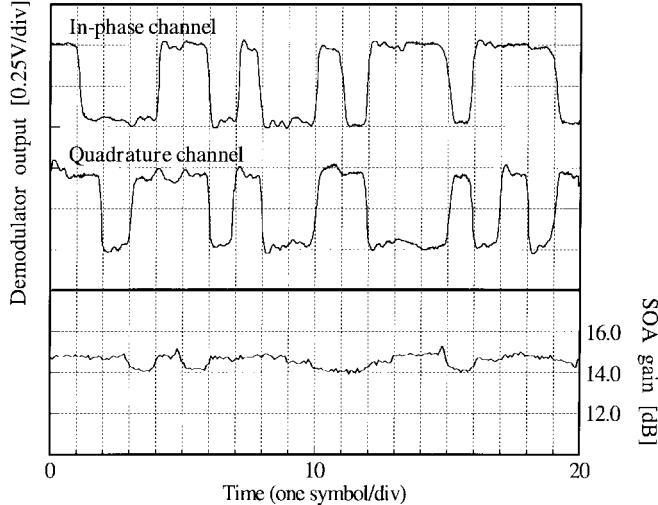


Fig. 9. Demodulated QPSK *I* and *Q* channel (upper traces) and SOA gain (lower trace) at 1 Gb/s.

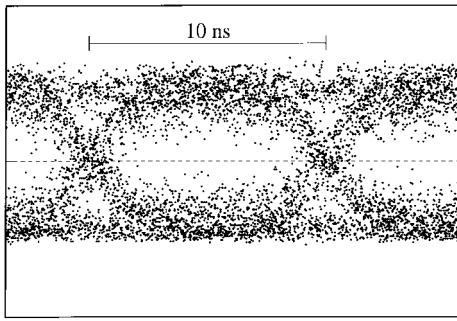


Fig. 10. Eye diagram for 200-Mb/s QPSK (*I* channel) through a PSK receiver with a 120-MHz noise bandwidth.

besides the noise, the eye diagram is well defined and does not show any other deteriorating effects. To further verify this, a 100-Mb/s PSK transmission has also been carried out. As seen from Fig. 6, PSK is less sensitive to phase noise than QPSK. Therefore, a very clean eye diagram is obtained, as shown in Fig. 11. It is clearly seen that the eyes of the two different experiments have the same general shape and only differ due to the noise. This confirms a well-behaved link operation.

D. Summary

The experiment demonstrates the LF-to-RF modulating functionality of RHD links. Such links may prove useful in applications where the LF signal is readily available. This is the case in most up-link systems. In these systems, the traditional modulator and up-converter equipment becomes unnecessary when RHD links are used instead of DD links. Naturally, a comparison of the two types of links must take this into account when considering the aspects of performance, cost, power consumption, etc.

In addition, the experiment demonstrates that SOA's can efficiently be used as high bit-rate *M*-ary PSK modulators. They require less modulation power than most other optical modulators and at the same time provide gain to boost the transmitter power [22]. The use of SOA phase modulators are

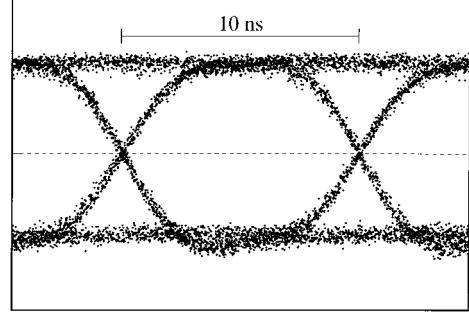


Fig. 11. Eye diagram for 100-Mb/s PSK through a PSK receiver with a 120-MHz noise bandwidth.

normally problematic due to their inherent AM and nonlinear PM. However, as demonstrated, both can be compensated in two-electrode devices [23].

VI. THE FREQUENCY UP-CONVERTING LINK

A. Experimental Setup

This experiment demonstrates frequency up-conversion of a 100-Mb/s PSK IF input signal at a carrier frequency of 2 GHz to an RF of 9 GHz [24]. The link setup is shown in Fig. 12. It consists of a PRBS generator, PSK microwave transmitter, O/E Tx unit, fiber-optic link, O/E Rx unit, DPSK microwave receiver, and a bit error rate (BER) detector. The Rx unit is the same as in the previous experiment. The Tx unit consists of the semiconductor laser OPLL RF generator and an external 2.5-GHz bandwidth LiNbO₃ phase modulator.

The IF input signal (cf. Fig. 13), is transmitted through the fiber-optic link phase modulated as a subcarrier onto one of the laser signals and is frequency up-converted in the Rx unit by the nonmodulated laser signal. The frequency up-conversion is determined by the frequency offset between the two lasers in the OPLL, which is chosen to be 7 GHz. As shown in Fig. 14, replicas of the input signal result at RF's of 5 and 9 GHz as sidebands to the optically generated 7-GHz carrier. The 9-GHz component of this signal is filtered and demodulated in the DPSK receiver.

B. Link Performance

The performance (in terms of BER) of the fiber-optic MW link is determined by the carrier-to-noise ratio (C/N) of the 9-GHz up-converted signal and by the phase noise of the optically generated microwave carrier. In this system, the C/N is determined by the optical modulation index (0.47 rad) which governs the power level and distortion of the up-converted signal, the received optical power from each laser (variable), and the thermal noise of the Rx unit (24 pA/√Hz). Further, the optically generated microwave carrier has an rms phase error of approximately 7° within the 80-MHz noise bandwidth of the DPSK microwave receiver due to a nonoptimum OPLL operation (cf. Fig. 6) during this experiment.

The BER is depicted in Fig. 15 versus the square root of the product between the received optical powers from the two transmitted laser signals. Further, an eye diagram

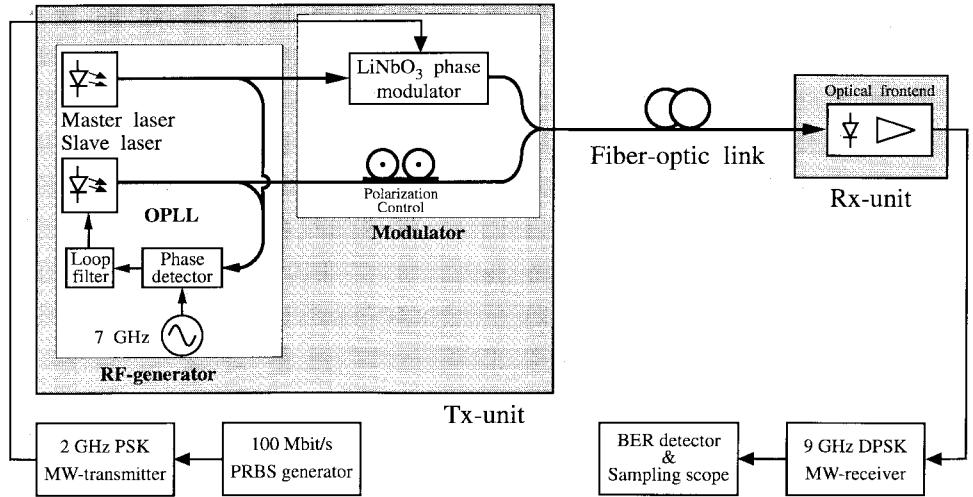


Fig. 12. Configuration of the frequency up-converting link.

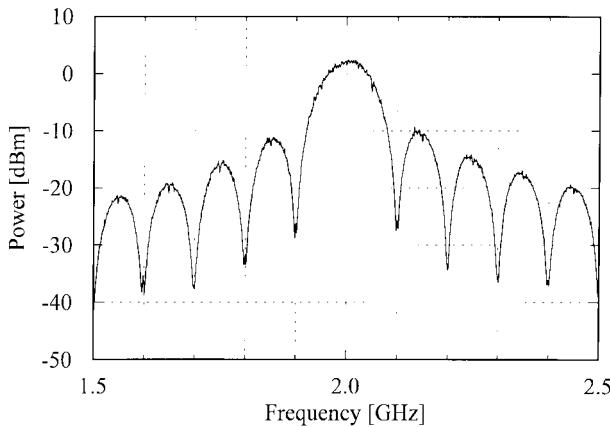


Fig. 13. Spectrum of the 100-Mb/s PSK 2-GHz IF input signal.

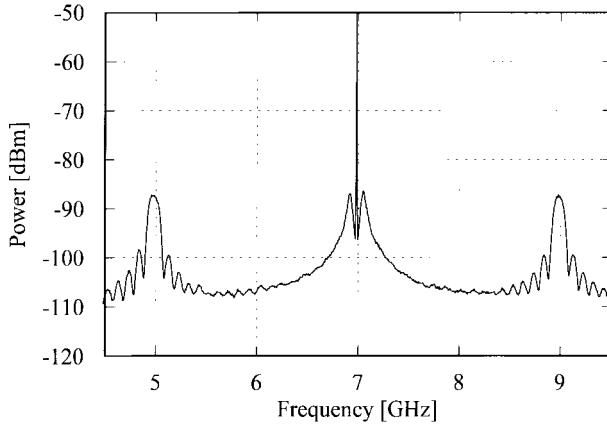


Fig. 14. Spectrum of the RF signal at the output of the Rx unit (RB = 3 MHz).

at a BER of less than 10^{-10} is shown in Fig. 16. The lower rippled trace, which is not present in a DPSK eye as measured directly at the demodulator output, is quite normal and is present due to the tight post-detection noise filtering. A PRBS of length $2^{31} - 1$ has been used for all the measurements. Fig. 15 gives a theoretical BER curve based on

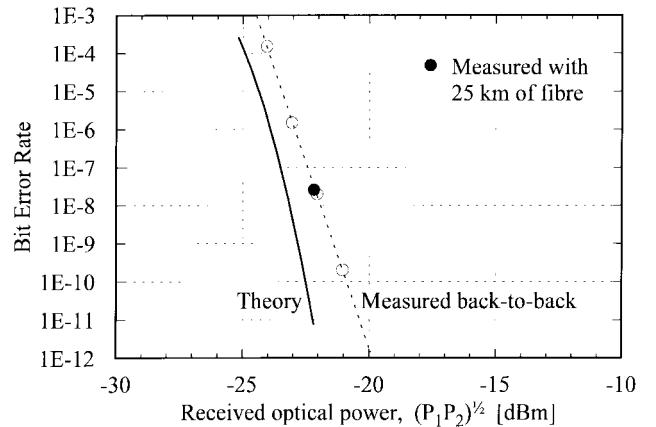
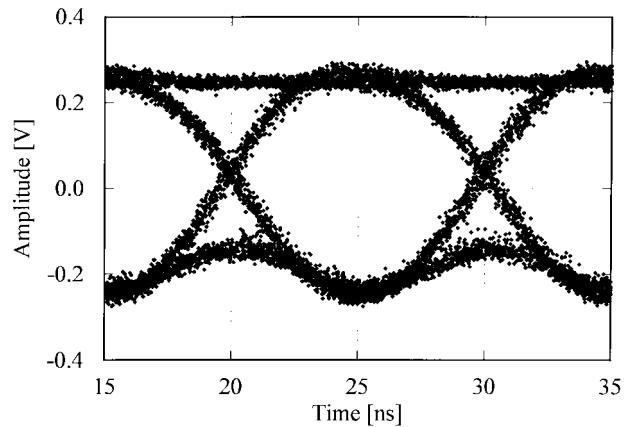


Fig. 15. Measured and calculated BER versus received optical power.

Fig. 16. Eye diagram at a BER of less than 10^{-10} .

the aforementioned noise parameters, a BER curve for optical back-to-back measurements (fiber-optic link of a few meters) and a BER value measured for transmission through 25 km of standard single-mode fiber. As seen, there is good agreement between the measured curve and the ideal theoretical curve. Further, the influence of the fiber, besides the 0.2-dB/km transmission loss, is negligible.

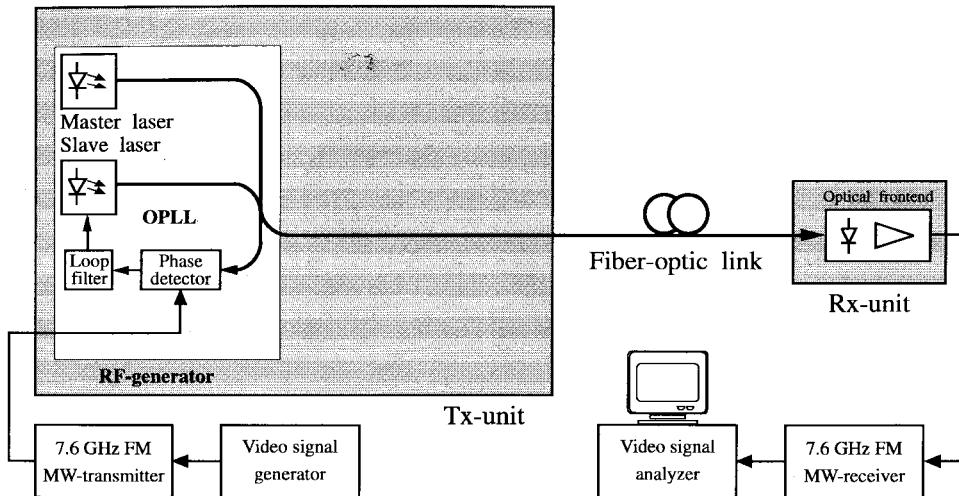


Fig. 17. Configuration of the transparent link.

C. Summary

The experiment demonstrates the IF-to-RF frequency up-converting functionality of RHD links. Although not demonstrated here, down-conversion is also achievable by proper selection of the input signal frequencies. Frequency converting links may prove useful in applications where the IF signal is readily available, as is most often the case. Further, the traditional up-converter and down-converter equipment becomes unnecessary when RHD links are used instead of DD links. Naturally, as mentioned for the modulating link, a comparison of the two types of links must take this into account when considering the aspects of performance, cost, power consumption, etc.

VII. THE TRANSPARENT LINK

A. Experimental Setup

This experiment demonstrates transparent transmission of a standard FM video 7.6-GHz radio-link signal [25]. The link setup is shown in Fig. 17. It consists of a video signal generator, microwave transmitter, O/E Tx unit, fiber-optic link, O/E Rx unit, microwave receiver, and a video-signal analyzer. The Rx unit is the same as in the two previous experiments, and the Tx unit consists of the semiconductor laser OPLL RF generator.

The RF input signal is a 7.6-GHz FM radio-link signal with a spectral width of 27 MHz that has been generated from a phase alternate line (PAL) video signal with a bandwidth of 6 MHz. This microwave signal is injected into the phase detector of the OPLL. The phase fluctuations of the two lasers will be correlated by the OPLL so that the phase and frequency of the laser beat signal after RHD tracks the phase and frequency of the RF input signal. In effect, the OPLL Tx unit modulates the information content of the RF input signal onto the optical signal of the locked laser and at the same time locks the laser to the master laser with a frequency offset equal to the carrier frequency of the RF input signal. The two laser signals are transmitted through

TABLE I
MEASURED PARAMETERS OF THE LINK EXPERIMENT (NA: NOT APPLICABLE)

Parameter	Back-to-back	Optical link	Requirements for 25-50 km links
Link gain:			
Insertion (0 km)	0 dB	-37 dB	—
Transmission (25 km)	—	-47 dB	—
Dynamic range	—	0 dB	—
Linearity:			
Differential gain	$\pm 1.4\%$	$\pm 1.5\%$	$\pm 2\%$
Differential phase	$\pm 0.1^\circ$	$\pm 0.3^\circ$	$\pm 1^\circ$
Noise:			
Noise figure	—	NA	—
C/N_0	122.7 dBHz	111.8 dBHz	—
Non-weighted S/N	63.4 dB	47.8 dB	—
Weighted S/N	69 dB	58 dB	60 dB

the 25-km fiber-optic link and the RF signal is recovered in the Rx unit by RHD. The recovered signal is demodulated in the microwave receiver and the demodulated video signal is analyzed. The transparent transmission can be performed for RF signals modulated in either frequency or continuous phase and with carrier frequencies within the operational range of the OPLL (here, 3–18 GHz). The exact modulation bandwidth capability depends in detail on the modulation format as well as several loop aspects which are outside the scope of this paper. However, in general, the modulation rate for any modulation format must be less than the loop natural bandwidth (here, 110 MHz), and the peak frequency deviation for frequency modulated signals must be less than the lock range of the loop (here, 175 MHz) [19], [26].

B. Link Performance

Normally, a transparent fiber-optic RF link is characterized through its gain, dynamic range, linearity, and noise. These are evaluated in the following based on the measured results given in Table I, together with results of an electrical back-to-back measurement (microwave transmitter to microwave receiver). For comparison, Table I also gives the requirements for main (25–50-km) radio FM TV links.²

²“A broadcasting engineer’s vade mecum,” *IBA Tech. Rev.* 10, May 1978.

C. Link Gain and Dynamic Range

The link was operated with a 10-dBm RF input signal and gave a -27-dBm RF output signal for a 0-km transmission and -37 dBm for a 25-km transmission. This gives a link insertion gain of -37 dB and a link transmission gain of -47 dB.

The optical power levels in the transmitter were optimized for optimum OPLL performance rather than for maximum transmission power so that only -15 dBm was put into the link from each laser. For the link presented here, the link gain is directly proportional to the product of the power of the two laser signals [19]. Therefore, the link gain can be significantly improved by increasing the optical output power of the transmitter. A 25-dB increase of the power from each laser from -15 to 10 dBm will result in a link gain improvement of 50 dB. This will increase the insertion gain from -37 to 13 dB and the 25-km transmission gain from -47 to 3 dB.

The link gain is also inverse proportional to the power of the input RF signal [19]. This is because a fixed input power level is required to pump the mixer in the phase detector to ensure a fixed OPLL operation [26]. As a result of this, the link gain can be improved by the use of a more efficient mixer requiring a lower pump power. However, it also means that the dynamic range of the link is very close to 0 dB as is normal for a PLL input [26].

D. Link Linearity

The linearity of the link is given in terms of the baseband-to-baseband differential gain and differential phase as measured on the 4.43-MHz color subcarrier in the video signal. These are traditionally used to characterize the linearity of an FM link.³ They include all contributions from amplitude response, group delay response, and AM/PM conversion. As seen, the optical link only introduces a negligible distortion of the video signal which is within the accuracy of the measurement setup. Further, the measured distortion levels are well within the requirements.

E. Link Noise

A noise figure cannot be defined for a transparent RHD link based on an OPLL transmitter. This is because PLL's can very efficiently recover input signals that are accompanied by a significant additive noise [26]. Consequently, the C/N density ratio (C/N_0) of the RF output signal is independent of the C/N_0 of the RF input signal, and an RF output signal with a high C/N_0 may be obtained even for an RF input signal with a rather poor C/N_0 . However, a too poor C/N_0 will result in the generation of additional phase noise on the RF output signal due to additive noise to phase noise conversion in the OPLL [26]. The amount of additional phase noise that can be tolerated sets the lower limit for the C/N_0 of the RF input signal.

The noise performance of the link must be evaluated from the signal-to-noise ratio (S/N) of the demodulated video signal. This takes all noise sources into account and is determined by

³"Differential gain and phase," Hewlett-Packard Applicat. Note 175-1, June 1974.

TABLE II
C/N DENSITY RATIOS OF THE OPTICAL LINK

Source	C/N_0 [dBHz]	$\Delta C/N_0$ [dB]
RF input signal	122.7	-0.9
OPLL E/O-O/E conversion		
RF output signal (0 km fiber)	121.8	-10.0
5 dB fiber loss		
RF output signal (25 km fiber)	111.8	-10.9
Total change		

the signal strength, additive noise, phase noise, and amplitude noise of the RF output signal.

As seen from Table I, the link is capable of delivering a studio-quality video signal with a weighted S/N of 58 dB which is very close to the 60-dB requirement. Further, it is seen that the optical link introduces a 15.6-dB reduction of the nonweighted S/N. Although the S/N requirements of FM TV links are normally addressed through the weighted S/N,² an assessment of the S/N reduction can only be performed using the nonweighted S/N values. This is because the weighting function may significantly alter the influence of the different noise sources.

The influence of the additive noise on the S/N can be easily distinguished from the other noise sources by measurement of the C/N_0 (signal strength over additive noise). The change in C/N_0 from input to output of the link has been shown in Table II. The C/N_0 value of the input signal is found from the back-to-back measured S/N.² This is valid because the signal from the MW transmitter has very low phase and amplitude noise. The C/N_0 of the optically generated RF output signal is governed by the available laser power, fiber loss, laser relative intensity noise (RIN) density at the frequency corresponding to the frequency of the RF signal, thermal noise of the optical receiver, and polarization-mode dispersion of the fiber (it reduces the RF signal strength). However, for the RF signal frequency and fiber length of this experiment, the polarization mode dispersion is of insignificant influence [1]. The C/N_0 values for the RF output signal are found from the measured signal strength, laser power, RIN, and thermal noise. As seen, the additive noise introduces a total C/N_0 reduction and thereby an S/N reduction of 10.9 dB. However, it must be noted that the C/N_0 reduction due to the fiber loss is fixed whereas the C/N_0 reduction/improvement due to the OPLL E/O-O/E conversion strongly depends on the C/N_0 of the RF input signal as previously explained. Consequently, for an RF input signal with a C/N_0 of 110 dBHz, a C/N_0 improvement of 11.8 dB would have been obtained due to the OPLL E/O-O/E conversion because the C/N_0 of the RF output signal would remain unchanged. Finally, the C/N_0 of the RF output signal can be increased by increasing the power from each laser. However, this C/N_0 improvement is not linear with laser power and an improvement limit exists due to the laser RIN [19].

Based on the S/N reduction due to additive noise, it is possible to identify the S/N reduction due to the remaining noise sources. The total S/N reduction is (from Table I) found to be 15.6 dB, and the S/N reduction due to additive noise is (from Table II) found to be 10.9 dB. This means that the phase

noise and the amplitude noise introduce an S/N reduction of 4.7 dB. The phase noise of the RF output signal depends on the laser phase noise, phase noise reduction efficiency of the OPLL, and chromatic fiber dispersion. However, for the RF signal frequency and fiber length of this experiment, the chromatic dispersion is of insignificant influence [2]. The amplitude noise of the RF output signal depends on the laser RIN density from zero to 27 MHz (the spectral width of the RF signal). This RIN is up-converted by the RHD to enter the RF output signal as amplitude noise. As found through measurements, it may be quite significant if the lasers are not properly isolated toward optical back-reflections [19]. Unfortunately, it is not possible to distinguish amplitude noise and phase noise in the measurements. Therefore, it cannot be determined how much of the 4.7-dB S/N reduction is caused by phase noise and how much is caused by amplitude noise.

Finally, it must be noted that the three noise sources (additive, phase, and amplitude) have very different influences on the signal. Therefore, an S/N improvement obtained by reducing one of the noise sources cannot compensate the S/N degradations introduced by any of the other noise sources.

F. Summary

The experiment demonstrates that the RHD link, when based on OPLL transmitters, can also be used for implementation of RF-to-RF transparent links. However, as shown, the nature of this link is significantly different from that of conventional RF-to-RF transparent links. These differences may be of significant advantage in some applications, e.g., if the input signal has a poor C/N_0 . Further, it must be realized that the performance of the link is independent of the frequency of the RF signal as long as the same OPLL performance is maintained.

Together with the two previous link experiments, this experiment demonstrates that fiber-optic MW links based on RHD can perform any of the three functionalities that are characteristic in radio systems. As opposed to the DD link, the RHD link can in many cases be optimized to the specific application. This may significantly influence performance, cost, power consumption, etc., and must be taken into account when comparing the two types of links.

VIII. CONCLUSION

The multifunctionality of MW links based on RHD has been discussed and experimentally demonstrated in this paper.

In a modulating link experiment, a 1-Gb/s baseband input signal has been QPSK modulated onto a 9-GHz RF signal in conjunction with fiber-optic transmission. Further, a frequency-converting link experiment has demonstrated up-conversion of a 100-Mb/s PSK input signal at 2 GHz to an RF output signal at 9 GHz with penalty-free transmission over 25 km of optical fiber. Finally, a transparent link experiment has demonstrated transmission of a standard FM video 7.6-GHz radio-link signal over 25 km of optical fiber without measurable distortion.

These three link experiments clearly demonstrate the three radio-system functionalities that are obtainable with RHD

links, as well as their feasibility. In many applications, modulating or frequency converting links may be much more desirable than transparent links. The RHD technique enables these, as opposed to the conventional DD-technique. When comparing DD links and RHD links this must be taken into account, and the entire system must be evaluated in its entirety from end to end.

All of the presented experiments have been performed with a dual-frequency laser transmitter based on optical offset phase-locked semiconductor lasers. The experiments have demonstrated the efficiency, flexibility, and feasibility of this type of transmitter that also has potential for both hybrid and monolithic O/E integration. Work on integration is in progress. A MMIC-based O/E phase detector has been implemented [27], [28], and a hybrid integrated and packaged OPLL is under construction [29]. Integration might eventually lead to cost reduction making fiber-optic MW links based on RHD attractive for future specialized MW systems.

ACKNOWLEDGMENT

The three-electrode DFB lasers for the transmitter were made by the Industrial Microelectronics Center, Kista, Sweden, the two-electrode SOA was made by Alcatel Alsthom Recherche, Marcoussis, France, and the optical fiber was supplied by Lycom, Brøndby, Denmark and the FM microwave radio-link equipment supplied by TeleDenmark, Tåstrup, Denmark.

REFERENCES

- [1] R. Hofstetter, H. Schmuck, and R. Heidemann, "Dispersion effects in optical millimeter-wave systems using self-heterodyne method for transport and generation," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2263–2269, Sept. 1995.
- [2] U. Gliese, S. Nørskov, and T. N. Nielsen, "Chromatic dispersion in fiber-optic microwave and millimeter-wave links," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1716–1724, Oct. 1996.
- [3] D. Wake, C. R. Lima, and P. A. Davies, "Optical generation of millimeter-wave signals for fiber-radio systems using a dual mode DFB semiconductor laser," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2270–2276, Sept. 1995.
- [4] M. Tamburini, M. Parent, L. Goldberg, and D. Stillwell, "Optical feed for a phased array microwave antenna," *Electron. Lett.*, vol. 23, no. 13, pp. 680–681, 1987.
- [5] C. L. Wang, Y. Pu, and C. S. Tsai, "Permanent magnet-based guided-wave magneto-optic Bragg cell modules," *J. Lightwave Technol.*, vol. 10, pp. 644–648, May 1992.
- [6] M. Izutsu, S. Shikama, and T. Sueta, "Integrated optical SSB modulator/frequency shifter," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 2225–2227, Nov. 1981.
- [7] G. H. Smith, D. Novak, and Z. Ahmed, "Technique for optical SSB generation to overcome dispersion penalties in fiber-radio systems," *Electron. Lett.*, vol. 33, no. 1, pp. 74–75, 1997.
- [8] J. J. O'Reilly, P. M. Lane, R. Heidemann, and R. Hofstetter, "Optical generation of very narrow linewidth millimeter wave signals," *Inst. Elect. Eng. Electron. Lett.*, vol. 28, no. 25, pp. 2309–2311, 1992.
- [9] H. Schmuck, R. Heidemann, and R. Hofstetter, "Distribution of 60 GHz signals to more than 1000 base stations," *Electron. Lett.*, vol. 30, no. 1, pp. 59–60, 1994.
- [10] L. Goldberg, H. F. Taylor, and J. F. Weller, "Microwave signal generation with injection-locked laser diodes," *Electron. Lett.*, vol. 19, no. 13, pp. 491–493, 1983.
- [11] L. Goldberg, A. M. Yurek, H. F. Taylor, and J. F. Weller, "35 GHz microwave signal generation with an injection-locked laser diode," *Electron. Lett.*, vol. 21, no. 18, pp. 814–815, 1985.
- [12] R. C. Steele, "Optical phase-locked loop using semiconductor laser diodes," *Electron. Lett.*, vol. 19, no. 2, pp. 69–70, 1983.

- [13] K. J. Williams, L. Goldberg, R. D. Esman, M. Dagenais, and J. F. Weller, "6-34 GHz offset phase-locking of Nd: YAG 1319 nm nonplanar ring lasers," *Electron. Lett.*, vol. 25, no. 18, pp. 1242-1243, 1989.
- [14] R. T. Ramos and A. J. Seeds, "Fast heterodyne optical phase-lock loop using double quantum well laser diodes," *Electron. Lett.*, vol. 28, no. 1, pp. 82-83, 1992.
- [15] U. Gliese, T. N. Nielsen, M. Bruun, E. Lintz Christensen, and K. E. Stubkjær, S. Lindgren, and B. Broberg, "A wideband heterodyne optical phase locked loop for generation of 3-18 GHz microwave carriers," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 936-938, Aug. 1992.
- [16] R. J. Pedersen, U. Gliese, B. Broberg, and S. Nilsson, "Characterization of a 1.5 μ m three-electrode DFB laser," in *Proc. 16th European Conf. Opt. Commun.*, Amsterdam, The Netherlands, Sept. 1990, pp. 279-282.
- [17] U. Gliese, E. Lintz Christensen, and K. Stubkjær, "Laser linewidth requirements and improvements for coherent optical beam forming networks in satellites," *J. Lightwave Technol.*, vol. 9, pp. 779-790, June 1991.
- [18] R. Gross and R. Olshansky, "Multichannel coherent FSK experiments using subcarrier multiplexing techniques," *J. Lightwave Technol.*, vol. 8, pp. 406-415, Mar. 1990.
- [19] T. N. Nielsen, U. Gliese, S. N. Nielsen, and K. E. Stubkjær, "Performance evaluation of fiber-optic microwave links," Dept. Electromagnetic Syst., Technical University of Denmark, R 590, ESA Contract Rep. 134212, Oct. 1994.
- [20] T. N. Nielsen, U. Gliese, J. Riishøj, K. E. Stubkjær, P. Doussiere, P. Grabedian, F. Martin-Leblond, J. L. Lafragette, D. Leclerc, and B. Fernier, "A Gbit/s QPSK optical microwave transmitter based on a semiconductor optical amplifier phase modulator and phase locked DFB lasers," in *Tech. Dig. Conf. Opt. Fiber Commun.*, San Jose, CA, Feb. 1994, pp. 114-115.
- [21] J. Riishøj, T. N. Nielsen, U. Gliese, "A 4 Gbit/s 2-level to 2 Gsymbol/s 4-level converter GaAs IC for semiconductor optical amplifier QPSK modulators," *IEEE J. Solid-State Circuits*, vol. 29, pp. 1277-1281, Oct. 1994.
- [22] T. N. Nielsen, U. Gliese, B. Mikkelsen, and K. Stubkjær, B. Fernier, P. Doussiere, and J.-L. Lafragette, "Characterization of high speed phase modulators based on semiconductor optical amplifiers," in *Tech. Dig. 2nd Topical Meeting Opt. Amplifiers Applicat.*, Snowmass Village, CO, July 1991, pp. 130-133.
- [23] T. N. Nielsen, N. Storkfelt, U. Gliese, B. Mikkelsen, T. Durhuus, K. E. Stubkjær, B. Fernier, F. Leblond, and A. Accard, "Cancellation of the inherent AM in semiconductor optical amplifier phase modulators," *Inst. Elect. Eng. Electron. Lett.*, vol. 18, no. 3, pp. 235-236, 1992.
- [24] U. Gliese, T. N. Nielsen, S. N. Nielsen, and K. E. Stubkjær, "Frequency up-shifting fiber-optic microwave link," in *Proc. IEEE MTT-S & LEOS Topical Meeting Opt. Microwave Interactions*, Abbaye de Vaux de Cernay, France, Nov. 1994, pp. 137-139.
- [25] T. N. Nielsen, U. Gliese, K. E. Stubkjær, T. Christensen, and H. Høgh, "Highly linear and transparent 3-18 GHz optical microwave link," in *Tech. Dig. IEEE MTT-S Int. Microwave Symp.*, San Diego, CA, May 1994, pp. 491-494.
- [26] A. Blanchard, *Phase-Locked Loops—Application to Coherent Receiver Design*. New York: Wiley, 1976.
- [27] M. Bruun, U. Gliese, A. K. Petersen, T. N. Nielsen, and K. E. Stubkjær, "A 2-10 GHz GaAs MMIC opto-electronic phase detector for optical microwave signal generators," in *Tech. Dig. IEEE MTT-S Int. Microwave Symp.*, San Diego, CA, May 1994, pp. 499-502.
- [28] ———, "A 2-10 GHz GaAs MMIC opto-electronic phase detector for optical microwave signal generators," *Microwave J.*, vol. 37, no. 8, pp. 94-100, 1994.
- [29] L. N. Langley, C. Edge, M. J. Wale, U. Gliese, A. Seeds, C. Walton, J. Wright, and L. Coryell, "Optical phase locked loops as signal sources for phased array communications antennas," vol. 3160, presented at the Proc. 42nd SPIE Annu. Meeting, San Diego, CA, July 1997, paper 31 60-17.



Ulrik Gliese was born in 1965. He received the M.Sc.E.E. and Ph.D. degrees from the Technical University of Denmark (DTU), Lyngby, Denmark, in 1989 and 1992, respectively.

Since 1989, he has worked with fiber-optics for microwave applications. From 1992 to 1995, he was a Senior Researcher at DTU on a post-doctoral fellowship. He was Work Package Manager and Sub-Contract Manager on several contracts with the European Space Agency and U.S. Army. He is currently Associate Research Professor and Project

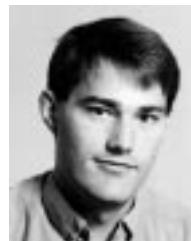
Manager for work on Optical Networks for Wireless Communications at the Center for Broadband Telecommunications, DTU. His research activities have covered coherent optical communication systems, microwave devices, characterization of advanced semiconductor lasers, OPLL's for generation of microwave to submillimeter-wave signals, laser phase noise reduction by phase conjugate feedback, optical modulation, O/E MMIC devices, fiber-optic microwave links, wireless ATM access systems, and mobile communication networks.



Torben Nørskov Nielsen was born in 1965. He received the M.Sc.E.E. and Ph.D. degrees from the Technical University of Denmark, Lyngby, Denmark, in 1991 and 1994, respectively.

Since 1991, he has worked with fiber-optics for microwave applications and has been Work Package Manager on several contracts with the European Space Agency. From 1994 to 1996, he was a Member of Technical Staff at Bell Laboratories, Lucent Technologies, Murray Hill, NJ, working on analog fiber-optic transmission systems. He is currently

a Member of Technical Staff at Bell Laboratories, Lucent Technologies, Crawford Hill, NJ, working on high-speed optical communication systems. His research activities have covered broad-band microwave amplifiers, modeling and characterization of SOA's, optical modulation with SOA's, OPLL's for generation of microwave to submillimeter-wave signals, laser phase noise reduction by phase conjugate feedback, O/E MMIC devices, fiber-optic microwave links, fiber amplifiers, and high-speed optical communication systems.



Søren Nørskov was born in 1966. He received the M.Sc.E.E. and Ph.D. degrees from the Technical University of Denmark (DTU), Lyngby, Denmark, in 1994 and 1997, respectively.

He is currently with Nokia Mobile Phones, Copenhagen, Denmark, working with ASIC design. His research activities have covered phase-locked loops for clock recovery in 10-20-Gb/s optical communication systems, fiber-optic microwave links, ATM traffic modeling, and access systems for ATM-based multimedia mobile communication networks. As part of the latter, he has been a Visiting Researcher at WINLAB, Rutgers University, New Brunswick, NJ.

K. E. Stubkjær (S'76-M'81), photograph and biography not available at the time of publication.