A Mobile Broad-Band Communication System Based on Mode-Locked Lasers

Clemens H. von Helmolt, Udo Krüger, Kirsten Krüger, and Gerd Grosskopf

***Abstract*—A concept is proposed for a pico-cellular network for broad-band mobile communication on a millimeter-wave basis. How microwave optical-signal-processing techniques based on mode-locked lasers (MLL's), optical modulators, and high-speed photo diodes (PD's) can advantageously be applied in the optical feeder lines of a pico-cellular network at 60 GHz is investigated. The external cavity MLL (at 81.25 GHz) used for the experiments showed an single-sideband (SSB) phase noise of −59 dBc/Hz at 100-Hz offset, when actively locked at 6.25 GHz. With the PD, and limited by the V-band mixer equipment, spectral harmonics up to 100 GHz could be detected. For the downlink configuration, a 400-MHz subcarrier is modulated with a 155-Mb/s data signal and upconverted to 62.9 GHz using an MLL and a fast PD. The upconverted sideband at 62.9 GHz was received with an optical power of −14.3-dBm at a bit-error-rate (BER) equal to 10^{-9} without any additional penalty due to transmitting the signal over 3 km of optical fiber. BER measurements at 155 Mb/s down to 10^{-11} were made. For the uplink, the digitally encoded RF signal is downconverted also by optical microwave signal processing. A 155-Mb/s data encoded 19.21-GHz signal is downconverted to 460 MHz using a mode-locked laser, an optical modulator, and a 600-MHz optical receiver front end. A receiver sensitivity of −24.5 dBm (BER equal to 10^{-9}) is demonstrated with the microwave signal being transmitted over a 1-m radio link and 3 km of optical fiber.**

***Index Terms*—Fiber optics, mobile networks, optical communication, optical microwave, radio in the local loop.**

I. Introduction

FUTURE mobile-communication systems should support data rates of 155 Mb/s and more, and because of the limits in available bandwidth at centimeter-wave carrier frequencies, the 60-GHz band is favorable. Due to the strong oxygen absorption in the 60-GHz band, small cells can be realized, potentially yielding a high frequency-reuse. Since the penetration depth at such high frequencies is small, in-house communication neighbor rooms are isolated by the walls.

The mobile network consists of a cluster of cells and a mobile switching center (MSC) serving mobile users via base stations (BS's). The MSC has to manage all traffic and needs connections to all BS's of its cluster, to all neighbor MSC's, and the public network. Fig. 1 shows a basic link structure in order to connect the mobile units (MU's) located in one cell with the MSC. All connections to and from the MSC are in fiber technique with separated lines for up- and downlink, because fiber techniques are able to carry a great data bandwidth with low transmission losses.

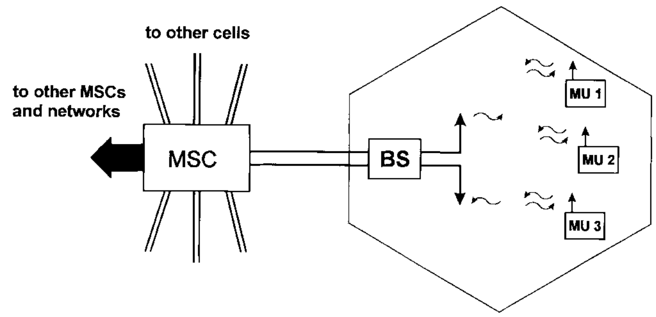

Fig. 1. Basic link structure, with BS = base station, MSC = mobile switching center, and MU = mobil unit.

However, the connection from the MSC to a BS and vice versa is also performed by a laser as transmitter, a transmission fiber, and a photo diode (PD) as receiver. It is expected to save costs if the laser/fiber/PD combination is not only used for transmitting the data signal, but also to translate the data signal into the microwave range in the downlink and to downconvert the microwave signal in the uplink.

For the downlink, different approaches for the optical generation and distribution of millimeter waves have been investigated so far. The highest frequencies at which the lasers in special arrangements can be modulated are in the region between 35–45 GHz [1], [2]. For the implementation of millimeter-wave systems with frequencies above 50-GHz, optical heterodyning is a promising technique in which two optical waves with a frequency spacing corresponding to the desired millimeter-wave frequency are heterodyned. The millimeter-wave signal is obtained at the output of the optic/millimeter-wave converter, mainly comprising a high-speed photo detector. In principle, the optical waves can be emitted either from two separate lasers (multiple optical-source technique [3]–[5]), or by use of special arrangements from one laser (single optical-source technique) like modulation-sideband technique [6], dual-mode laser [7], harmonic upconversion in nonlinear lasers [8], [9], mode-locked lasers [10], [11], or pulsed lasers [12]. With the different generation methods, the millimeter-wave signal depicts different properties concerning applicable modulation formats, phase noise [13], tunability, and sensitivity to fiber dispersion [14].

In the uplink configuration, a downconversion by mixing of the microwave signal is required, which might look attractive to be optically done by the use of a remotely operated optical modulator without an optical uplink transmitter at the BS.

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Possible photonic solutions for microwave optical mixing are reported in [15]–[18] using two intensity modulators. A more general overview of optical-microwave signal processing is given in [19].

In our system concept mode-locked laser (MLL) transmitters are used both for the upconversion to millimeter-wave frequencies in the downlink and for the generation of a LO signal, which is used for the downconversion in the uplink. For the downlink, there is a mode-locked laser (MLL) in the MSC and a high bandwidth PD in the BS. The PD generates the microwave frequency by heterodyning the frequency comb of the MLL. The information band on an intermediate frequency (IF) subcarrier is applied at the MSC by direct modulation of the MLL. For the uplink, we propose a remotely biased optical modulator at the BS leading to a mostly *passive* BS without any millimeter-wave oscillator and optical transmitter.

The main advantage of the proposed system concept is that *no* (for passive mode locking) or only a *lower* millimeter-wave-frequency oscillator (typical $<$10 GHz for active mode locking) is necessary for generating signals in the *higher* millimeter-wave-frequency range (up to 100 GHz, mainly limited by the speed of the PD). For active mode locking, the MLL performs an n-tupler function, which means that the voltage-controlled oscillator (VCO) driver frequency (set to the repetition rate of the MLL) is only the nth part of the desired millimeter-wave frequency.

A further advantage results from the application of a subcarrier, which allows every modulation format and, by selecting different subcarrier frequencies, also allows additional transmission capacity for up- and downlink if the linearity and dynamic requirements can be met.

In addition to the upconverted information band, the electrical downlink signal at the BS contains discrete spectral lines at multiples of the MLL repetition rate. An appropriate line can be selected and used as an LO signal for the uplink millimeter-wave receiver at the BS. With the uplink IF output signal of that receiver, a remotely biased optical modulator can be driven in order to allow transmission to the MSC.

Alternatively, if high-speed optical modulators would become available at moderate costs, a photonic mixing technique for millimeter-wave downconversion could be applied [19], [20].

A dispersion-shifted fiber (DSF) for the feeder line is necessary to minimize the dispersion penalty using a 1.5-μm MLL as the optical source. With a 1.3-μm MLL as the optical source, the DSF can be replaced by a standard single-mode fiber.

In this paper, we present key experiments for the system concept mentioned above. In Section II, the MLL properties and the spectral properties of the optically generated millimeter-wave signals are discussed. Section III deals with transmission experiments for the downlink and the uplink. Finally, in Section IV we present a short conclusion.

II. MLL

The external cavity MLL used in our experiments comprises an 150-line/mm grating and a saturable absorber. It generates nearly transform limited pulses of $<$1-ps width [21]. Its repetition rate is set to 6.250 GHz, being locked to an HP 83650 synthesizer.

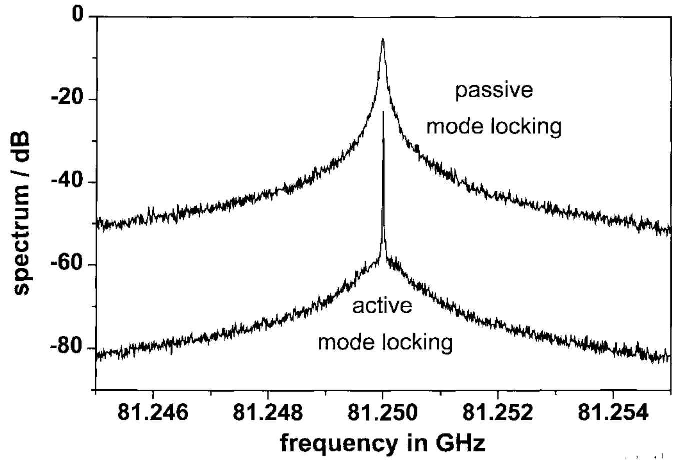

Fig. 2. Electrical PD spectra for an active and passive MLL at 81.250 GHz.

Fig. 2 shows the electrical output spectra of a fast PD at 81.25 GHz detecting the light emitted by the MLL. For these measurements, the electrical signal is downconverted with a V-band mixer and an LO set to 72.5 GHz. The IF at 8.75 GHz is then measured with a spectrum analyzer with 1-kHz resolution. The signal-to-noise ratio is always $>$16 dB. In the upper curve, the MLL is passively mode locked, whereas in the lower curve the laser is actively locked. In the latter case, close to the carrier, the phase noise of the synthesizer dominates, whereas for frequency offsets above 50 kHz from the carrier the MLL determines the total phase noise. This was confirmed in separate measurements at 81.25 GHz resulting in a measured single-sideband (SSB) phase noise of $-$59 and $-$70 dBc/Hz at 100-Hz and 100-kHz offset frequencies from the carrier, respectively.

The relative intensity noise (RIN) and the noise of the MLL at the fundamental are reported in [20], a general overview over MLL configurations and their properties is given in [22].

III. TRANSMISSION EXPERIMENTS

In order to demonstrate the feasibility of the proposed system concept, transmission experiments were made applicable to the downlink situation with fiber-optic upconversion and to the uplink situation with fiber-optic downconversion. In A and B, the experimental results for the downlink are given for external and direct MLL modulation, respectively. The external modulation [23] with improved results is reported here in order to allow a comparison with the results of the direct MLL modulation. For the uplink, experimental results are reported in C related only to a photonic-mixing technique. These experiments were performed in order to allow for future comparison with electrical mixing experiments.

A. Downlink Experiment with External Modulation of the MLL

The principle of the downlink transmission setup is shown in Fig. 3. The MLL is actively locked, and its center wavelength is tuned to 1542 nm, which corresponds to the dispersion

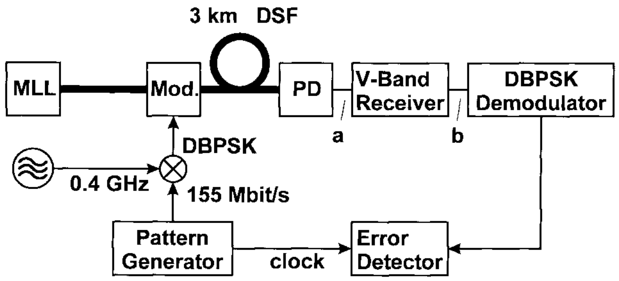

Fig. 3. Principle of the transmission setup for the downlink experiment with external modulation.

minimum of the DSF. The output signal of the MLL is fed to an optical intensity modulator (Mod.). The information to be transmitted over the radio channel is supplied by the pattern generator feeding a 155-Mb/s differentially encoded nonreturn-to-zero pseudorandom bit sequence (NRZ PRBS) into a double-balanced mixer. This mixer generates the differentially coherent binary PSK (DBPSK) signal [24] on a 400-MHz subcarrier supplied from a synthesizer. The short pulses of the MLL are intensity modulated with the DBPSK signal and subsequently transmitted over 3-km DSF to be detected by a fast PD (NEL KEPD1310VPG). The amplitude modulated sequence of short electrical pulses at the output of the PD has spectral components up to frequencies $>$100 GHz. One DBPSK sideband is detected by the V-band receiver and is fed to the error detector after demodulation in the DBPSK demodulator.

In order to compensate the 10-dB insertion loss of the external modulator (HP 83 422A), the insertion loss of the fiber, of the attenuator used for bit-error-rate (BER) measurements, and of the various optical connectors, the MLL output signal of -13 dBm is boosted by an erbium-doped fiber amplifier (EDFA) followed by a 1-nm optical bandpass filter. These details are not shown in Fig. 3, but a comparable MLL–EDFA-filter configuration can be found in [23, Fig. 3].

The spectra of the signals at points a and b in Fig. 3 are shown in Fig. 4(a) and (b), respectively. In Fig. 4(a), the spectrum of the transmitted signal is displayed between 0–22 GHz, when measured at the electrical output of the photo diode. The three strong discrete comb lines at 6.25, 12.5, and 18.75 GHz, respectively, are generated by the photo detection of the optical pulses. At 400 MHz and symmetric to each comb line with 400-MHz offset, the modulated sidebands of the DBPSK subcarrier appear. The spectral components centered at 0.8, 1.2, and 1.6 GHz belong to the second, third, and fourth harmonic of the modulated subcarrier. These harmonics come up because of the strong driving of the optical modulator with its $\sin^2$-shaped characteristic. Due to the electrical modulation format, all even harmonics are reduced to discrete lines. All baseband spectral components find their replica symmetric to each comb line.

The V-band receiver in Fig. 3 consists of a waveguide mixer (Spacek MV-U) and an LO realized by a Quadrupler (HP 83 557A) driven by an HP 83 623 synthesizer. In order to detect the upconverted sideband at 62.9 GHz, the LO frequency is set to 63.36 GHz resulting in an IF of 460 MHz. The detected IF spectrum is shown in Fig. 4(b). In Fig. 5, the BER (PRBS $2^{23}-1$) is shown versus average optical power. A sensitivity of -15 dBm for a BER equal to 10^{-9} was achieved. Compared with the back-to-back measurement, there is no penalty observed due to transmitting the signal over 3 km of dispersion shifted fiber. However, an (uncritical) adjustment of the MLL center wavelength to the dispersion minimum of the DSF is required in order to avoid interference effects at millimeter-wave frequencies due to dispersion.

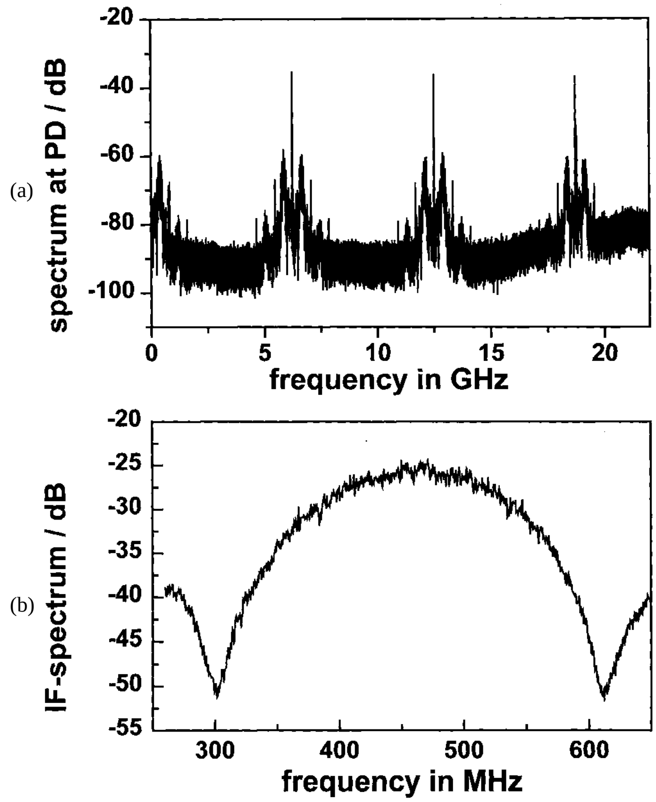

Fig. 4. (a) Electrical spectrum after the photo diode. (b) IF spectrum after the V-band receiver.

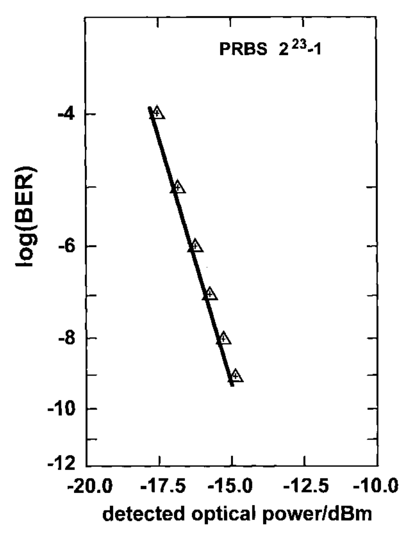

Fig. 5. BER measurements for the downlink experiment with external modulation.

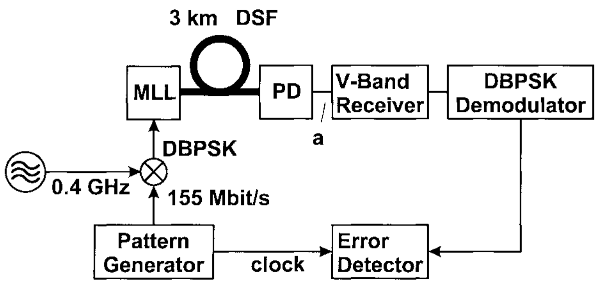

Fig. 6. Principle of the transmission setup for the downlink experiment with direct modulation.

B. Downlink Experiment with Directly Modulated MLL

An attractive variant of an MLL fiber-optic upconverter is shown in Fig. 6. It is identical to Fig. 3 with the exception that the external optical modulator is omitted and the MLL is directly modulated in intensity by the DBPSK-modulated 400-MHz subcarrier. The spectrum of the photo current at point a in Fig. 6 is very similar to the spectrum shown in Fig. 4(a) with the exception that the third and fourth harmonic of the modulation signal do not appear due to a slightly better linearity at direct modulation.

With the directly modulated MLL, different transmission experiments were done where the MLL was generally passively mode locked. In a first experiment, the directly modulated MLL was set to $\lambda = 1532$ nm at a repetition rate of 6.25 GHz. The upconverted sideband at 62.9 GHz was detected with the V-band receiver in a back-to-back measurement without any optical filtering of the approximately 3-nm-wide MLL spectrum. The measured BER curve is shown in Fig. 7, indicated by 1. A sensitivity of -16 dBm at a BER equal to 10^{-9} was achieved. Due to the stability of this setup without any polarization-dependent devices as external modulators or optical filters, BER measurements down to 10^{-11} were made, additionally reflecting the repetition-rate stability of the passively mode-locked laser.

In a second experiment, the MLL was set to $\lambda = 1542$ nm. Its modulated output signal was boosted by an EDFA followed by a 1-nm optical bandpass filter in order to compensate for the fiber, connector, and attenuator losses. With the LO frequency of 63.36 GHz, the upconverted sideband at 62.9 GHz is selected. The BER measurements both back to back and with transmission over the 3-km-long DSF are shown in Fig. 7, curve 2. The sensitivity for a BER equal to 10^{-9} was -14.3 dBm, without any additional penalty due to the fiber-optic transmission. However, a slight polarization dependence of the optical filter could be observed. The curve is given for optimized polarization. The penalty of roughly 2 dB with respect to curve 1 is most probably due to a lower modulation index because the laser is operated at higher dc current, the influence of the 1-nm filter (optical 3-dB bandwidth) on the millimeter-wave mixing product, and the additional amplified spontaneous emission (ASE) noise of the EDFA.

For curve 3, the V-band receiver is tuned up to 69.15 GHz. The penalty of about 2 dB, with respect to curve 2, is due to the frequency response of the PD and V-band receiver.

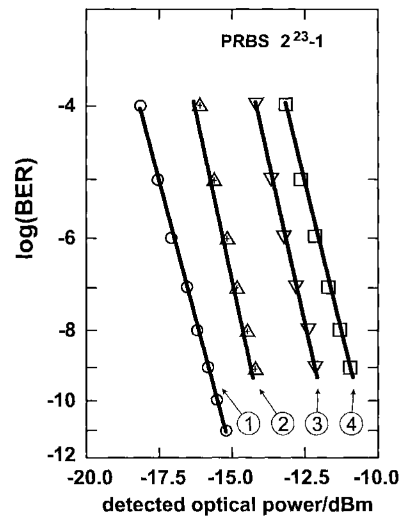

Fig. 7. BER measurements for the downlink experiment with direct modulation. 1 = MLL at 1532 nm, directly modulated, without optical filter, back to back, 62.9 GHz; 2 = MLL at 1542 nm, directly modulated, with optical filter (1 nm), 3-km DSF and also back to back, 62.9 GHz; 3 = MLL at 1542 nm, directly modulated, with optical filter (1 nm), back to back, 69.15 GHz; 4 = MLL at 1532 nm, directly modulated, with optical filter (3 nm), back to back, 80.86 GHz.

In a fourth experiment, the MLL was set to 1532 nm. Its output signal was again boosted by an EDFA followed by a 3-nm optical bandpass filter. In order to detect the modulation sideband even at 80.86 GHz (390-MHz subcarrier frequency) the V-band mixer Spacek MV-U was operated above its specified value of 75 GHz. The first LO was set to 72.5 GHz, so that the modulation sideband was downconverted to the first IF at 8.36 GHz. With a second mixer and a second LO set to 7.977 GHz, the signal was downconverted to the second IF of 383 MHz, which could be processed by the DBPSK demodulator. Curve 4 of Fig. 7 shows the measured BER performance. The penalty of 5 dB with respect to curve 1 is mostly due to the response of the PD and receiver circuitry.

In order to finish the part related to upconversion experiments it should be noted that the transmission length was not limited to 3-km length because there was no dispersion penalty observed for the properly adjusted laser.

Comparing the sensitivity of -15 dBm (BER equal to 10^{-9}) for external modulation with -14.3 dBm (BER equal to 10^{-9}, Fig. 7, curve 2) for direct modulation, both methods result in a similar microwave generation efficiency at the receiver. The small difference of 0.7 dB most probably arises from the nonoptimum modulation depth of the directly modulated MLL during the experiments leading to curve 2 of Fig. 7. Curve 2 is chosen because in contrast to curve 1 an EDFA and a 1-nm filter was inserted in the link experiment which is comparable to the external modulation experiment. However, additionally taking into account the insertion loss, the polarization dependence, the high drive power, and the costs of an external modulator, the direct MLL modulation is, in most cases, superior to the external modulation.

C. Uplink Experiment

The principle of the experimental uplink setup is shown in Fig. 8 [25]. It consists of hardware related to the functions of

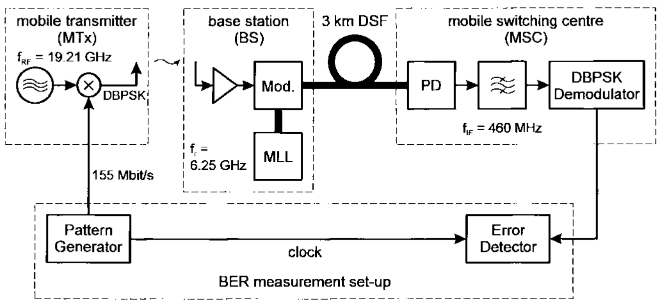

Fig. 8. Principle of the uplink setup including fiber optic downconverter, with DSF = dispersion shifted fiber, PD = photo diode; DBPSK = differential binary phase-shift keying.

the mobile transmitter (MTx), the BS and the MSC, a radio and a fiber-optic link of 1 m and 3 km, respectively, and a BER measurement setup. The MTx is substituted by an RF synthesizer (HP 83 650), a mixer, and an antenna. A 155-Mb/s DBPSK signal at a microwave carrier is transmitted to the BS using horn antennas. The received microwave signal at the BS drives after appropriate amplification an optical intensity modulator (Mod.) modulating the light pulses emitted by the external cavity MLL. The microwave signal is thus optically sampled at the repetition rate of the MLL (in the experiment at $f_r = 6.25$ GHz). After transmission over 3-km DSF, the optically sampled microwave signal is detected with the PD being located at the MSC. Its electrical output contains spectral components at f_r and its multiples as well as at all mixing terms with the information band centered at $f_{\rm RF}$. The downconverted band at $f_{\rm IF} = f_{\rm RF} - 3f_r = 460$ MHz is filtered, DBPSK demodulated, and fed to the error detector.

In the experiment, the MLL is located at the BS in order to omit the additional experimental effort for the polarization handling of a remotely biased optical modulator. However, the polarization handling is no principle drawback because passive methods are well known to eliminate the polarization sensitivity of fiber-optic modulators [26], [27]. A polarization-switching technique [27] induced by the MLL repetition rate may especially result in the lowest additional effort for the polarization handling.

Due to constraints in the speed of the optical modulator available in the laboratory (HP 83 422A), the principle of the downconversion is demonstrated at a microwave-carrier frequency of 19.21 GHz. The optical modulator is driven with the DBPSK modulated microwave carrier by bridging in a first experiment the radio link in Fig. 8 with a coaxial cable. The MLL used for downconversion is configured as described above and set to $\lambda = 1532$ nm. The MLL signal is then boosted by an EDFA followed by a 1-nm filter (not shown in Fig. 8). At the MSC, the spectrum of the PD output signal is measured. The result is shown in Fig. 9 for an average optical power of -16 dBm. The three strong discrete lines at 6.25, 12.5, and 18.75 GHz, respectively, belong to the pulses sampling the information band at 19.21 GHz. All other spectral parts separated from the noise are mixing products including the desired downconverted band at 460 MHz. Around each strong discrete line and at frequencies $<$0.3 GHz, noise bands appear which are based on phase noise and RIN [20].

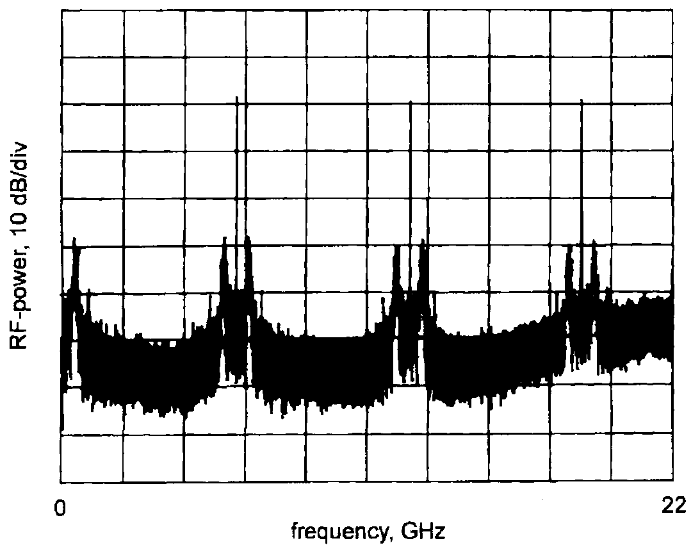

Fig. 9. Detected RF spectrum at the MSC after opto-electronic conversion (resolution bandwidth is equal to 3 MHz).

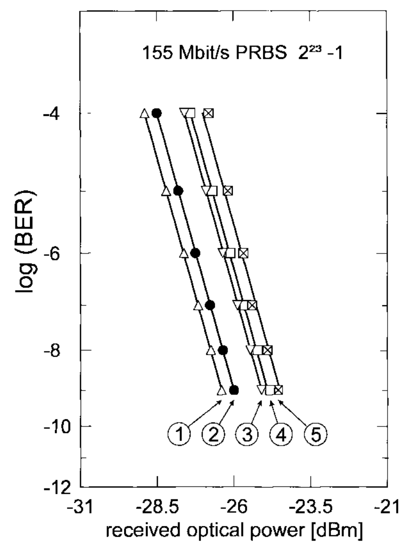

Fig. 10. BER measurements for the uplink experiment, with 1 equal to an HP-ECL (not mode locked), $f_{\rm RF} = 460$ MHz, without radio link and DSF; 2 equal to an MLL, $f_{\rm RF} = 460$ MHz, without radio link and DSF; 3 equal to an MLL, $f_{\rm RF} = 19.21$ GHz, without radio link and DSF; 4 equal to an MLL, $f_{\rm RF} = 19.21$ GHz, without radio link, with DSF; 5 equal to an MLL, $f_{\rm RF} = 19.21$ GHz, with radio link and DSF.

For BER measurements, a commercially available p-i-n/preamplifier module is used as optical receiver at the MSC. This module has a 3-dB bandwidth of 600 MHz and a sensitivity of -27 dBm for a 622-Mb/s signal. In Fig. 10, the measured BER (155 Mb/s, PRBS $2^{23} - 1$) is shown against received optical power at the MSC for different experimental configurations related to Fig. 8. In curve 1, the microwave-carrier frequency $f_{\rm RF}$ is set to 460 MHz, the MLL is replaced by an HP external cavity laser (ECL) tuned to the MLL center wavelength, and the radio link as well as the 3-km fiber link are bridged. The measured sensitivity of -26.4 dBm (BER equal to 10^{-9}) agrees reasonably well with the receiver sensitivity mentioned above taking into account several penalties as $<$100% modulation depth by the optical modulator, nonoptimum filtering of the 600-MHz low-pass filter used as an IF filter, and nonoptimum DBPSK demodulation at the MSC. In curve 2, we have the same configuration as in curve 1 except that the ECL is replaced by the MLL. The additional penalty of 0.4 dB is most probably due to the RIN of the MLL. In curve 3, there is the same configuration as in curve 2 except that f_{RF} is set to 19.21 GHz and the downconverted signal is measured. The additional penalty of 0.9 dB is probably due to the reduced modulation depth achievable with this optical modulator at higher frequencies. In curve 4, the 3-km DSF is in addition inserted, resulting in a dispersion penalty of about 0.2 dB. This slight penalty arises because the MLL center wavelength was detuned from the dispersion minimum of the fiber by about 10 nm. In curve 5, there is the same configuration as in curve 4 except that, in addition, the 1-m radio link is used. The slight penalty of 0.4 dB compared to curve 4 is most probably due to the noise of the additional microwave preamplifiers used, in order to compensate for the loss of the radio link. However, the radio link is of course sensitive to reflections, which may explain the spreading of the measured values.

It should be noted that the transmission and downconversion quality was independent of the kind of operation of the MLL, i.e., active or passive mode locking. This result is reasonable because low phase-noise microwave signals are generated by the MLL after photodetection. The 81.25 GHz in Fig. 2 exhibits a linewidth of only 53 kHz even for the passively locked MLL. This linewidth is approximately one order smaller than 0.33% of the bit rate, which leads to a 1-dB phase-noise penalty [13] for DBPSK systems.

IV. Conclusion

We have proposed a system concept for a pico-cellular broad-band mobile network based on optical microwave signal processing using mode-locked lasers, optical modulators, and high-speed photo detectors. System experiments and phase-noise measurements have been made at carrier frequencies up to 80 GHz. Transmission experiments at 155 Mb/s were carried out with fiber-optic upconversion. At 62.9 GHz, a sensitivity of -16 dBm (optically) for an BER equal to 10^{-9} was achieved with a passively locked, directly modulated MLL. It has been shown that the direct MLL modulation is superior to external modulation because it resulted in a similar receiver sensitivity, but the costs and the insertion loss of an external modulator can be saved. The dispersion problem was solved by the application of a DSF, however the system can be realized at 1.3-μm wavelength allowing standard single-mode fiber to be applied. Due to the good phase-noise properties of the millimeter-wave signal generated by the MLL-PD arrangement there was no related penalty observed for the up and downconverted 155-Mb/s data signals. Using fiber-optic downconversion, a data encoded 19.21-GHz signal was received at 460 MHz. A receiver sensitivity of -24.5 dBm (BER equal to 10^{-9}) was demonstrated with the microwave signal being transmitted over 1-m radio link and 3 km of optical fiber. Since high-speed optical modulators are reported now with a bandwidth >100 GHz, the proposed techniques can be applied up to this frequency range because the limitations given by the optical sampling pulsewidth of about 1 ps begin at frequencies >300 GHz for the MLL used.

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