Optical Microwave Generation and Transmission Experiments in the 12- and 60-GHz Region for Wireless Communications

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***Abstract*— Experiments on the optical generation and transmission of millimeter-wave radio signals are reported. The millimeter-wave signals are generated by heterodyning the optical spectral lines of a mode-locked laser (MLL) or of two or more semiconductor lasers at an optic/millimeter-wave converter (OMC). 70-, 140-, and 155-Mb/s data transmission experiments have been carried out successfully in optical single-channel and multichannel systems at radio frequencies of 12 GHz and 58–70 GHz. Bit-error-rate measurements yielded error-free transmission and no error floor was observed. A monolithically integrated tunable optical-signal source was developed and used for generating the millimeter-wave signals. This technology promises a high cost-saving potential for applications in radio-over-fiber systems.**

***Index Terms*— Broad-band communication, millimeter-wave radio communication, mobile communication, optical fibers, phase noise, semiconductor lasers, sideband injection locking.**

I. Introduction

MICROWAVE signals in cellular broad-band mobile communication networks can favorably be generated and distributed by optical techniques. In principle, these techniques have already been investigated for optical control of phased-array antennas, characterization of photodetectors (PD's) and phase locking of millimeter-wave oscillators and are now being applied to wireless communications.

The generation and transmission of millimeter-wave radio signals by optical means is of special interest for future pico-cell broad-band mobile communication systems, especially for systems operating at frequencies of 60 GHz [1]–[3].[1] Prerequisites for the implementation of these systems are reliable low-cost components and technological principles. Here, the combination of lightwave and millimeter-wave techniques is a promising solution. Since a laser diode and a photodiode are required for the optical feeder link between the control station (CS) and the base stations (BS's) (Fig. 1), the millimeter-wave signal can be optically generated, offering a variety of advantages, including a cost reduction due to no millimeter-wave oscillators and modulators necessary in the numerous BS's.

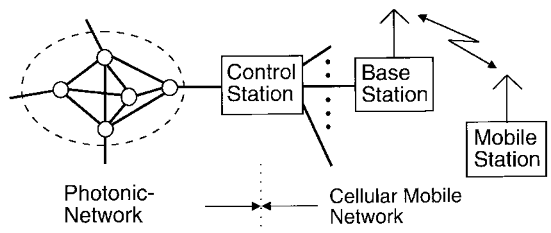

Fig. 1. Network architecture of a mobile and photonic network.

After some general remarks in Section II concerning optical millimeter-wave techniques, we describe in Section III experiments on data transmission with optically generated carriers at 60–70 GHz, a two-channel experiment and the application of a monolithically integrated optical-signal source are reported. In Section IV, two experiments with optical sources generating low phase-noise millimeter-wave signals are described in which a mode-locked laser (MLL) and sideband injection locking was used.

II. Optical Millimeter-Wave Techniques

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 [4]–[6]. For the implementation of millimeter-wave systems above 50 GHz, optical heterodyning is a promising technique. The frequency spacing of the optical waves corresponds to the desired millimeter-wave frequency. The millimeter-wave signal is obtained at the output of the optic/millimeter-wave converter (OMC), which mainly comprises a high-speed PD and a low-noise amplifier. Thus, OMC's in the BS and optical sources in the CS are key components which must be developed in a very cost effective technology.

A. Optic/Millimeter-Wave Converters

The PD of the OMC must be able to detect the beat signal of the incoming optical waves. Two types of PD's, two-port devices, and three-port devices are considered. Two-port devices are PD's such as p-i-n PD's [7]–[9],

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metal–semiconductor–metal (MSM)-PD's [10], and Schottky barrier PD's [11]. With a waveguide p-i-n PD, an electrical bandwidth of 75 GHz was measured using an optical heterodyne technique, and 110 GHz were determined by electrooptical sampling. The measurements were carried out at 1.55-μm optical wavelength [12]. To increase the conversion efficiency, and by this the system performance, the PD should be combined with low-noise amplifiers. As a first step, separate chips of photodiodes and amplifiers were combined in hybrid technology, depicting a responsivity of more than 1 mA per mW optical input power [13]. On the other hand, as the most promising technology for low-cost OMC's, the monolithic microwave integrated circuit (MMIC) process offers the advantage of integrating both the PD and the amplifier on the same chip, e.g., on InP technology [14]. Great efforts are carried out to develop PD's with high efficiency using three-port devices heterojunction bipolar transistor's (HBT's) high electron-mobility transistors (HEMT's) or MESFET's [15]–[17]. In [17], experiments with pseudomorphic AlGaAs/InGaAs HEMT's were reported. The HEMT's were integrated with multistage MMIC amplifiers or with antenna circuits. An optically generated continuously tunable 49–67-GHz millimeter-wave generation was demonstrated. The optical wavelength was at 0.632 μm. In [18], the feasibility of a 50-GHz subcarrier transmission link using the HBT-PD in the 1.3-μm wavelength range has been demonstrated. Compared to a p-i-n PD, the same responsivity, flatness, and signal-to-noise (SNR) were obtained. These experiments showed that MMIC-compatible devices could be utilized for OMC's.

B. Optical Sources, Frequency Stability, and Phase Noise

In principle, the optical waves can be emitted either from two separate lasers (multiple optical-source technique [19]–[23]), or by use of special arrangements from one laser (single optical-source technique) like modulation sideband technique [24]–[27], dual-mode laser [28], FM-modulated laser in conjunction with fiber dispersion, harmonic upconversion in nonlinear lasers [29]–[31], MLL's [32], [33], or pulsed lasers [34]. With the different generation methods, the millimeter-wave signal depicts different properties concerning applicable modulation formats, phase noise, and tunability.

The spontaneous emission and absorption of photons in the laser cavity causes phase noise which may deteriorate the system performance. In the following, we distinguish between optical waves with correlated and uncorrelated phase-noise terms which are heterodyned at the OMC. With correlated optical waves, a millimeter-wave signal with low phase noise is obtained. In case of the single optical-source technique, the phase-noise terms of the optical waves are inherently correlated. On the other hand, when using multiple optical sources with free-running lasers, the phase-noise terms are uncorrelated, yielding millimeter-wave signals with poor spectral purity known as a linewidth problem in a coherent system [35]. Different methods to obtain low phase-noise signals or to cancel the phase-noise influence have been reported, e.g., phase-noise cancellation at the OMC [36] or phase-noise cancellation by feedforward compensation [37]. The phase-noise terms of the optical waves can be correlated, e.g., using an optical phase-locked loop (PLL) [38]–[41], applying sideband injection locking [20], [42], [43] or combinations of both [44], [45], thus the phase noise vanishes in the millimeter-wave domain.

Concerning the frequency stability of the millimeter-wave signal, the stabilization of the optical waves, e.g., by using gas absorption lines, is not sufficient for radio-over-fiber systems. Therefore, usually only the difference frequency is stabilized by an opto-electronic automatic frequency control (AFC) loop, as shown in the experiment in Section III. High accuracy is obtained with optical PLL's which could also be used for phase-noise suppression. Other approaches for frequency stabilization are the injection-locking technique, in particular sideband injection locking and techniques which apply optical harmonic upconversion like MLL's.

III. EXPERIMENTS APPLYING THE MULTIPLE OPTICAL-SOURCE TECHNIQUE WITH UNCORRELATED PHASE-NOISE TERMS

This technique is used in coherent optical communications where at the receiver site the data signal is mixed with the signal of the local oscillator laser in order to improve the receiver sensitivity and the selectivity. In radio-over-fiber systems, this principle is applied to generate the millimeter-wave signal. However, the local oscillator laser, now depicted as reference laser (LDR), is located in the CS together with the signal laser (LDS). Moreover, the transmitted powers of both lasers LDS and LDR at the OMC input are of the same order of magnitude. Furthermore, an OMC is required, which depicts only a comparatively narrow bandwidth centered around the millimeter-wave carrier.

The current $i_{\rm ph}$ at the PD output for an frequency shift keying (FSK) modulated signal is given by

$$\begin{aligned} i_{\rm ph}(t) &= R\cdot P_S + R\cdot P_R + 2\cdot R\cdot\sqrt{P_S\cdot P_R} \\ &\quad\cdot\cos\left[\omega_{mm}(t) + d(t)\cdot\Delta\omega\cdot t + \Phi(t)\right] + n(t) \end{aligned}$$

where R is the responsivity of the PD, P_S and P_R are the optical powers of LDS and LDR at the PD, $\omega_{mm}/2\pi$ is the millimeter-wave frequency, $d = \pm 1$ for a transmitted 1 and 0, respectively, $\Delta\omega/2\pi$ is the frequency deviation, $\phi(t)$ is the phase noise, and $n(t)$ represents an additive noise term.

The advantage of the multiple-source technique is that only a relaxed modulation speed of the signal laser is necessary (given by the data rate), while the millimeter-wave signal is generated by the beat signal between two lasers. Due to the fast tunability of the lasers over a large optical bandwidth, a high-frequency flexibility is obtained.

In the following, we describe experiments with two different optical transmitter types; in the first case, the lasers are mounted on separate heat sinks, while in the second case, the lasers are monolithically integrated on a single photonic integrated circuit (PIC). A simplified arrangement of a mobile broad-band communication system is used, which enables the demonstration of the basic principles.

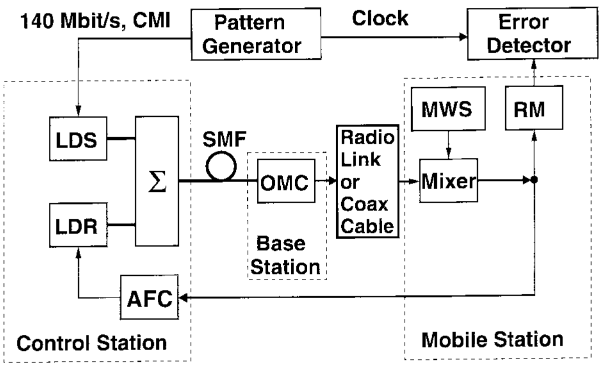


Fig. 2. Principle of the experimental setup. LDS: signal laser. LDR: reference laser. OMC: optic/millimeter-wave converter. MWS: millimeter-wave source. RM: receiver module. AFC: automatic frequency control. SMF: single-mode fiber.

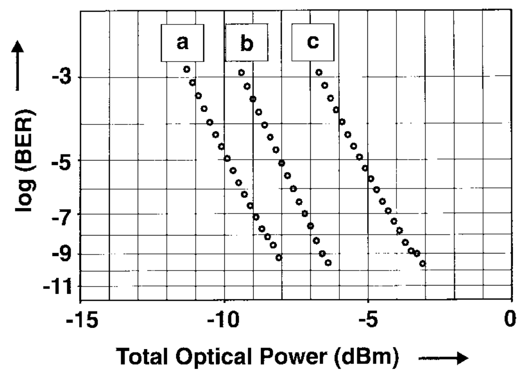


Fig. 3. BER versus total optical power at the input of the OMC with 140-Mb/s line-coded CMI data, PRBS with a wordlength of $2^{23} - 1$, CPFSK modulation for different experimental conditions. Experimental setup of Fig. 2: Curve a at 63 GHz via 12-km standard SMF. Curve b at 70 GHz via 10-m standard SMF. Curve c at 63 GHz via 10-m standard SMF and a radio link.

A. Optical Millimeter-Wave Experiments at 60–70 GHz Using Separate Lasers

Two distributed feedback (DFB) lasers (GEC-Marconi LD 4804, $\lambda = 1.54$ μm) LDS and LDR were used for generating the millimeter-wave carrier between 60–70 GHz (Fig. 2). The signal-laser LDS was directly modulated by a 140 Mb/s line-coded coded mark inversion (CMI) signal with a pseudo random binary sequence (PRBS) with a word length of $2^{23}-1$. The laser emitted a continuous phase FSK (CPFSK) signal. The optical output signals of both lasers were adjusted to be equal in power and polarization. The optical waves were combined and transmitted via a standard single-mode fiber (SMF) to the OMC (New Focus photodiode 1014). The millimeter-wave signal was led to a mixer (Millitech) driven by a millimeter-wave source (MWS, HP 83557A) providing the mixer local oscillator signal. The receiver module (RM) contained an IF amplifier at 1–2 GHz, followed by a delay-line discriminator, and a low-pass filter (160 MHz). The demodulated signal was than fed to a bit-error detector. Fig. 3 shows the BER versus the total optical power at the OMC input for different experimental conditions. At 63 GHz, the millimeter-wave signal was transmitted via 12 km of standard SMF between CS and BS (curve a) or via 10-m SMF and a radio link using horn antennas with 24-dB gain and a free-space attenuation of approximately 10 dB (curve c). At 63 GHz, an optical power of -8 dBm was required for a BER of 10^{-9}, resulting in an electrical power at the OMC output of approximately -50 dBm. For both short transmission lengths via optical fiber, no remarkable influence of polarization mode dispersion [46] was observed. Experiments have also been carried out (curve b) at 70 GHz. BER values below 10^{-9} were measured for all data transmissions, and no error floor was observed. Due to laser phase noise, the unmodulated millimeter-wave carrier depicted a linewidth of approximately 4 MHz. Hence, in order to maintain a BER below 10^{-9}, a frequency shift of the CPFSK modulation of approximately 400 MHz was necessary, resulting in a transmission bandwidth of approximately 0.7 GHz.

The millimeter-wave frequency was stabilized by AFC loop, which consisted of a frequency discriminator and a proportional integrate differentiate (PID) control circuit. It stabilized the center frequency of the IF signal, depicting a linewidth of 4 MHz within approximately ± 100 kHz. The PID output signal was used to control the reference laser frequency via its injection current.

B. Optical Millimeter-Wave Two-Channel Experiment

In mobile communication systems, multichannel performance is important. In the past, optical transmission systems using high-density optical frequency division multiplexed (FDM) signals have been investigated worldwide by many groups. In these systems at the receiver site, only the optical channel carrying the desired data is selected, e.g., by optical heterodyning [47]–[50] or filtering and direct detection [51]. In optical subcarrier multiplex (SCM) systems in which each optical wave is modulated by several subcarriers at the receiver site, one optical carrier is selected by optical means while the desired subcarrier channel is selected in the millimeter-wave or microwave domain [5], [52], [53]. In contrast to that, the photo current for the simultaneous conversion of an optical FDM signal with k channels to a millimeter-wave FDM signal can be described by the following expression (only the components of the desired millimeter-wave frequency band are shown):

$$i_{\mathrm{ph,\,mm}}(t) = 2\cdot R\cdot\sqrt{P_R}\cdot\sum_k\Big[\sqrt{P_{S,\,k}}\cdot\cos\big(\omega_{mm,\,k}(t)+d_k(t)\cdot\Delta\omega\cdot t+\Phi(t)\big)\Big]+n(t).$$

In the two-channel experiment, the optical waves originated from three separate lasers (GEC-Marconi LD 4804) depicted as signal lasers (LD1, LD2) and reference laser (LDR) (Fig. 4). The optical frequencies of LD1 and LD2 were separated from the reference frequency of LDR by the desired millimeter-wave frequencies near 12 GHz. For the data transmission, each signal laser was CPFSK modulated by a 140 Mb/s line-coded CMI data signal with a frequency shift between 1–0 of 550 MHz, resulting in a similar spectrum, as shown in [54]. The optical waves of the three lasers were combined (Σ) and transmitted via a fiber (length 10 m) to the OMC (HP 11 982A, conversion efficiency 300 mV/mW$_{\mathrm{optical}}$). The resulting microwave signal transmitted to the mobile station

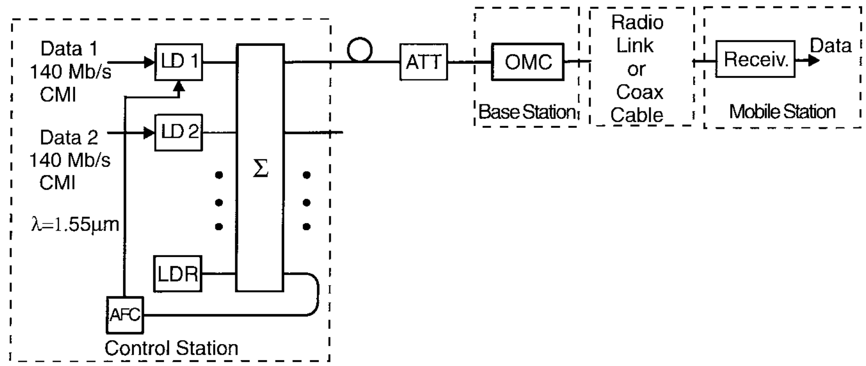
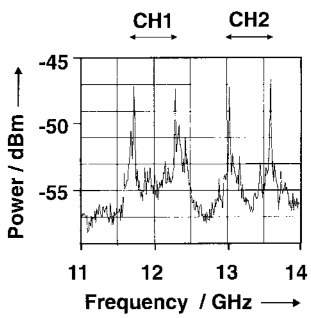
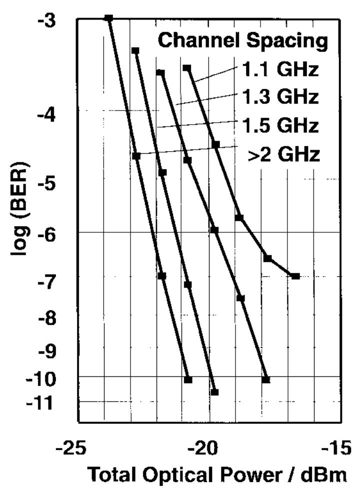


Fig. 4. Principle of the experimental setup for the two-channel experiment. LD1, 2: signal lasers. LDR: reference laser. OMC: optic/millimeter-wave converter. AFC: automatic frequency control. ATT: optical attenuator. SMF: single-mode fiber.



(a)



(b)

Fig. 5. (a) Spectrum of two modulated carriers in channels 1 and 2 (resolution bandwidth = 3 MHz), 140-Mb/s line-coded CMI data, PRBS with a wordlength of $2^{23} - 1$, CPFSK modulation, channel spacing 1.27 GHz, frequency shift 550 MHz. (b) BER versus total optical power at the OMC for different spacings of channels 1 and 2. Experimental setup of Fig. 4: 2 × 140-Mb/s line-coded CMI data, PRBS with a wordlength of $2^{23} - 1$, CPFSK modulation, the powers of LD1 and LD2 measured at the ATT were set to -9 dBm, respectively, the power of LDR was set to -5 dBm.

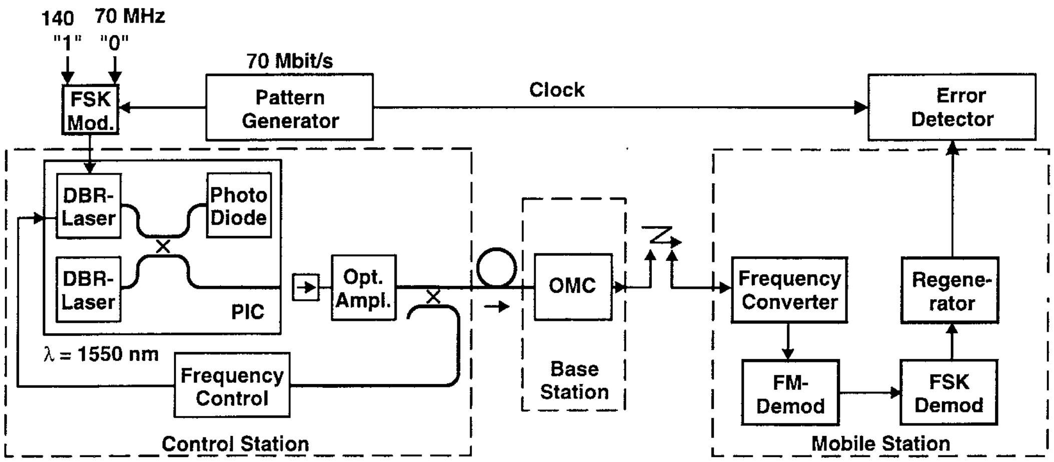
(MS) comprised both channels CH1 and CH2. Fig. 5(a) shows the electrical spectrum at the OMC output measured by an SA (HP 8565E) with a resolution bandwidth of 1 MHz. In this example, the channel spacing is 1.27 GHz. Fig. 5(b) shows the BER measurements in the test channel versus the total optical power at the OMC for different channel spacings. The BER measurements were carried out without radio link. The powers of LD1 and LD2 were set to -9 dBm each, and the power of LDR was set to -5 dBm, respectively. The optical powers were measured at the attenuator input (ATT). The electrical power $P_{el,\,50\,\Omega}$ in milliwatts at the 50-Ω OMC output for channel 1 is given by the normalized equation

$$\left(\frac{P_{el,\,50\,\Omega}}{\text{mW}}\right) = 3.6 \cdot \left(\frac{P_{\text{LD1}}}{\text{mW}}\right) \cdot \left(\frac{P_{\text{LDR}}}{\text{mW}}\right)$$

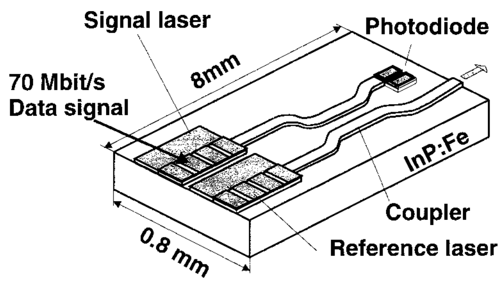
where P_{LD1} and P_{LDR} are the optical powers of LD1 and LDR given in milliwatts. For example, at BER $= 1 \cdot 10^{-9}$, an optical power from LD1 and LDR of -21 dBm was required at the input of the PD. For that, the optical ATT was adjusted to 17.5 dB, which resulted in a millimeter-wave power of -43.5 dBm at the OMC output. For channel spacings larger than 2 GHz, no degradation due to crosstalk in the test channel CH1 was observed. When the channel spacing was decreased by changing the temperature of LD2, a penalty was measured due to spectral overlap of the modulation sidebands. For the low optical power of -21 dBm at the OMC input at BER $< 10^{-9}$ and channel spacings >2 GHz, the influence of nonlinear distortions was of minor importance [55]–[57].

C. Optical Millimeter-Wave Experiments Using a Monolithically Integrated Tunable Optical-Signal Source

The following experiment demonstrates the potential of the monolithic integration for PIC's in pico-cell systems. The experimental setup containing a PIC module as a tunable optical-signal source is shown in Fig. 6(a). The PIC [Fig. 6(b)] consists of two tunable four-section DBR lasers, an optical 3-dB coupler, and a photodiode for monitoring purposes. All components are integrated on a semi-insulating InP:Fe substrate. The properties of the PIC and its fabrication are described in [21], [58], [59]. The currents in the four sections of each laser were optimized with respect to output power, modulation characteristics, and phase noise. Because the IF linewidth was 20 MHz, a double-modulation scheme was used [49]. The frequency of the signal laser was modulated via the phase section by a subcarrier which was FSK switched between 70 (logical zero) and 140 MHz (logical one). The transmission experiments were carried out with 70-Mb/s PRBS data signals in the nonreturn to zero (NRZ) format with a wordlength of $2^{23} - 1$. The two optical carriers generated by



(a)

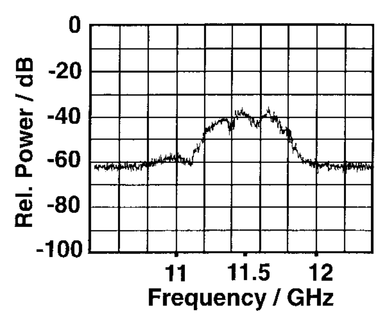


(b)

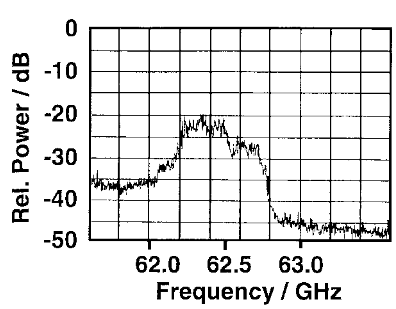
Fig. 6. (a) Principle of the experimental setup for millimeter-wave generation using a PIC module as tunable optical-signal source. (b) Schematic three-dimensional view of the PIC.

the PIC were transmitted via a fiber to the OMC in the BS. The total output power launched into the fiber was −12 dBm. The frequencies of the PIC signal laser and PIC reference laser differed in the two experiments by the desired millimeter-wave frequencies of 11.5 and 62.5 GHz, respectively. In the BS, the millimeter-wave signal at the OMC output was amplified and transmitted via a 1-m line of sight (LOS) radio link in the laboratory to the mobile heterodyne receiver. The horn antennas depicted a gain of 18 dB. The mobile receiver comprised a low-noise frequency converter at the input and an FM/AM converter followed by an FSK demodulator. After signal regeneration, the 70-Mb/s data stream was obtained. At the carrier frequency of 11.5 GHz, BER's of less than 10^{-10} have been achieved. Fig. 7 shows the measured spectra of the FM/FSK modulated millimeter-wave signals centered around 11.5 and 62.5 GHz. In both cases, the millimeter-wave carrier is frequency modulated by the subcarrier with a frequency shift of approximately 700 MHz. This frequency deviation was required in order to overcome the influence of phase noise. The shapes of the spectra are very similar, although the spectrum at 62.5 GHz depicts an asymmetrical shape due to the frequency response of the mixer amplifier prior to the SA.

This experiment demonstrates the feasibility of monolithically integrated optical sources for radio over fiber systems. The main advantage of this device compared with a hybrid solution is a uniform thermal ambience, which considerably reduces the costs for external temperature-control systems. The temperature coefficient of the generated millimeter-wave



(a)



(b)

Fig. 7. Spectra of the FM/FSK modulated carrier. Modulation: 70 Mb/s PRBS, wordlength of $2^{23} - 1$. (a) Carrier frequency 11.5 GHz. (b) Carrier frequency 62.5 GHz.

remains below 5 MHz/K, indicating the stable operation of the device. A further advantage is that only one optical isolator at the fiber/chip interface is needed. In addition, no polarization

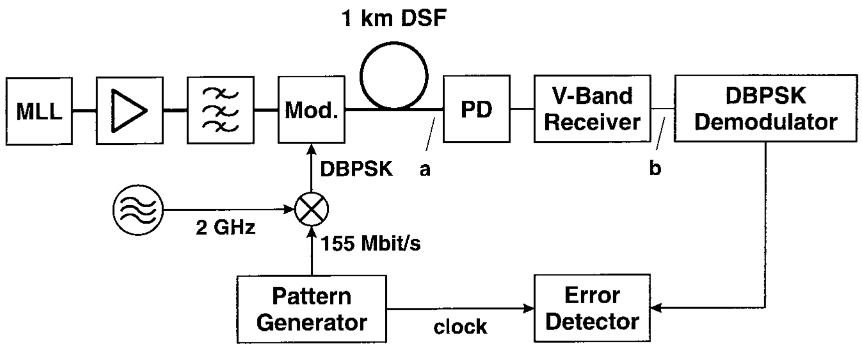


Fig. 8. Principle of transmission setup with a MLL as transmitter.

controllers are required because the states of polarization are parallel and given by the waveguide geometry on the PIC.

IV. Experiments Applying Optical Heterodyne Techniques with Correlated Phase-Noise Terms

In the experiments described so far, the uncorrelated phase-noise terms of the optical waves caused millimeter-wave linewidths of approximately 4 and 20 MHz, respectively. For mobile broad-band transmission systems with narrow channel-spacing bandwidth, efficient modulation formats should be used requiring high spectral purity carriers. According to the recommendations in [3], the following values for the single sideband (SSB) phase noise are desirable, i.e., < -68 dBc/Hz at 10 kHz, -84 dBc/Hz at 100 kHz, and -100 dBc/Hz at 1 MHz. Different approaches to reach this goal by optical means have been published so far.

In the following experiments, the application of two methods is demonstrated. The single optical-source technique applies a MLL where the phase-noise terms are inherently correlated. The other method we used is suitable for multiple optical sources. It applies sideband injection locking in order to correlate the phase-noise terms of the laser signals to be heterodyned.

A. Optical Millimeter-Wave Generation and Data Transmission with a Mode-Locked Laser

The principle of the transmission setup is sketched in Fig. 8. The output signal of an MLL, boosted by an erbium-doped fiber amplifier (EDFA) with subsequent narrow-band filtering ($\sim$ 1 nm), was fed to an optical intensity modulator (Mod.) [32]. The information to be transmitted over the radio channel was supplied as a substitute by the pattern generator feeding a 155-Mb/s differentially encoded NRZ PRBS signal to a double-balanced mixer. This mixer generated the differentially coherent binary PSK (DBPSK) signal on a 2-GHz subcarrier supplied from a synthesizer. The short pulses of the MLL were intensity modulated with the DBPSK signal and subsequently transmitted over 1 km of dispersion-shifted fiber (DSF) to be detected by a fast photodiode (New Focus 1014). The amplitude modulated sequence of the short electrical pulses at the output of the photodiode had spectral components up to frequencies $>$75 GHz. One DBPSK sideband was detected by the V-band receiver and was fed to the error detector after demodulation in the DBPSK demodulator.

The external cavity MLL comprising an 150-lines/mm grating and a saturable absorber generated nearly transform limited pulses of $<$ 1-ps width [60]. Its center wavelength was tuned to 1536 nm and its repetition rate was adjusted to 6.250 GHz being locked to an HP 83650 synthesizer.

Fig. 9 shows the RF spectrum of the synthesizer at 50 GHz and of the actively MLL at its eighth harmonic using an HP 8565E SA. The electrical-signal power in both cases was -40 dBm and the SA was set to 1-Hz resolution bandwidth. Since the sensitivity of the instrument used assured $>$ 27-dB SNR at -100-dBm input power and 0-dB input attenuation, the noise traces in Fig. 9 are presumed to be due to phase noise. The measured phase noise of -55 dBc/Hz at 100-Hz offset from the 50-GHz carrier was dominated by the synthesizer and the spectrum-analyzer properties. However, for offset frequencies $>$ 400 Hz, additional phase noise of the MLL can be seen. In a different setup using a preselected mixer, the MLL phase noise was measured at 62.5 GHz to be -66 dBc/Hz at 100-kHz offset [22].

In order to avoid interference effects at millimeter-wave beat frequencies due to dispersion, the spectral width ($>$ 3 nm) of the optical frequency comb was reduced to $\sim$ 1 nm in the optical bandpass filter. The spectra of the signals at points a and b in Fig. 8 are shown in Fig. 10(a) and (b), respectively. In Fig. 10(a), the optical power spectrum of the transmitted signal is displayed between 0–22 GHz, as obtained by an HP 71400 lightwave signal analyzer containing a calibrated optoelectronic converter and an electrical SA. The ordinate values are given in optical decibels, which are calculated from the electrical measurement by the instrument. The three strong discrete lines at 6.25, 12.5, and 18.75 GHz, respectively, were generated by the photo detection of the optical comb signal. At 2 GHz and symmetrically to each comb line with 2-GHz offset, the sidebands of the DBPSK modulated subcarrier appear.

The V-band receiver in Fig. 8 consisted of a waveguide mixer (Spacek PV-5) and local oscillator realized by a Quadrupler driven by an HP 83623 synthesizer. In order to detect the upconverted sideband at 58.25 GHz, the local oscillator frequency was set to 58.024 GHz, resulting in an IF of 226 MHz. The detected IF spectrum is shown in Fig. 10(b). In Fig. 11, the BER (PRBS, $2^{23}-1$) versus average optical power is shown. Compared with the back-to-back measurement there

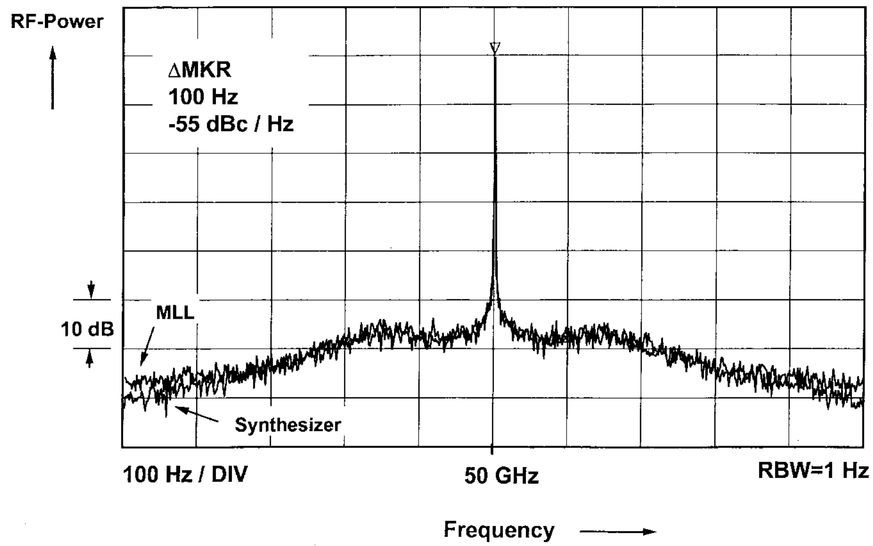


Fig. 9. Measured signal and noise at 50 GHz (for the generated millimeter-wave according to Fig. 8 and for the synthesizer used).

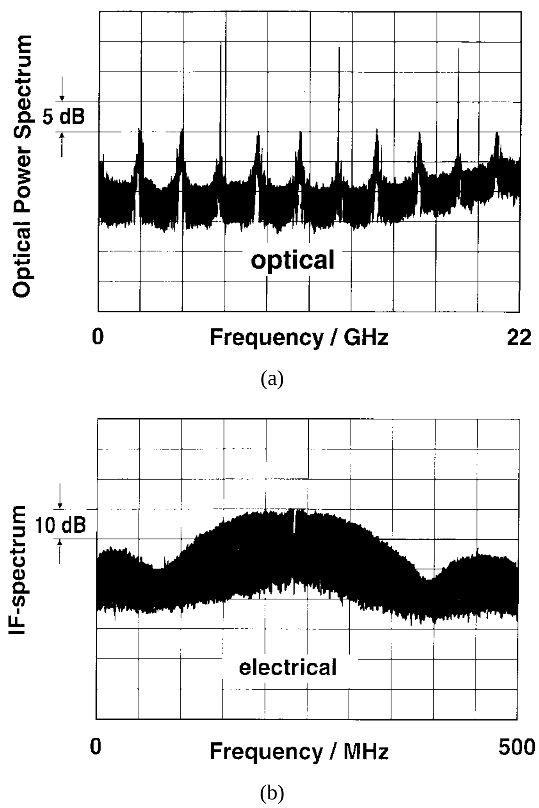


Fig. 10. (a) Optical power spectrum (point a in Fig. 8). (b) IF spectrum (point b in Fig. 8).

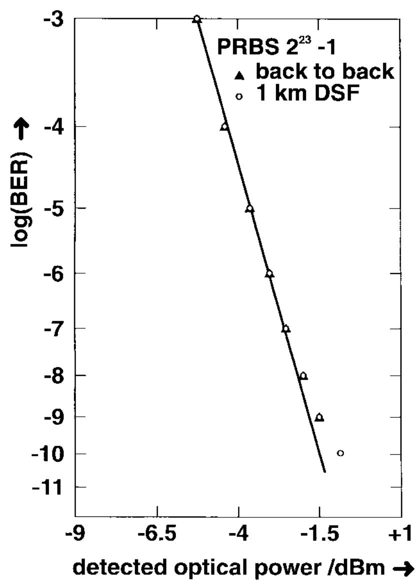


Fig. 11. BER measurements with the setup of Fig. 8.

is no penalty observed due to transmitting the signal over 1 km of optical fiber. The high optical power required at the photodiode was due to several penalties: 17 dB (electrical) loss at 58 GHz due to photodiode bandwidth limitations, 6 dB (electrical) loss due to the photodiode internal 50-Ω shunt, 9-dB SSB noise figure of the mixer IF preamplifier unit, insufficient local oscillator power and nonoptimum electronics.

We see the following advantages of the proposed principle. The MLL performs the desired n-tupler function (here, $n = 9$), therefore, only a moderate frequency (here, 6.25 GHz) voltage-controlled oscillator (VCO) driver is required. The electrical subcarrier allows every modulation format of the radio channel to be applied. With the subcarrier frequency, a precise offset of different radio frequency channels can be realized.

B. Optical Millimeter-Wave Generation with Sideband Injection Locking

The second method which was investigated for the generation of low phase-noise millimeter-wave signals applied optical sideband injection locking [20], [42], [43], [61], [62]. The master laser (LDM, Fig. 12) was modulated via its injection current by a synthesizer (OSC1) at 3.125 GHz. LDS and LDR were injection locked to the -10th and $+10$th modulation sidebands, depicting a frequency spacing equal to 62.5 GHz $(20 * f_{\mathrm{OSC1}})$. The phase-noise components in both injection locked lasers were correlated (co-phasal) so

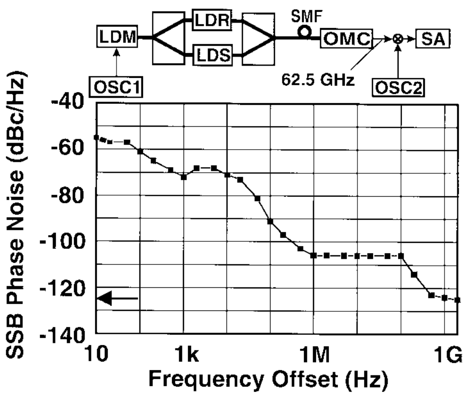


Fig. 12. SSB phase-noise measurement at 62.5 GHz applying the sideband injection-locking technique. The arrow indicates the noise level of the combination of SA and OSC2. Inset: Principle of the experimental setup. OSC1: 3.125 GHz. OSC2: 59.5 GHz.

that the phase noise was canceled after heterodyning at the OMC. The millimeter-wave signal at the OMC output was down converted and fed to a spectrum analyzer (SA). The millimeter-wave signal depicted the SSB phase noise versus the frequency offset measured after down conversion to 3 GHz. Values of < -70 dBc/Hz and < -90 dBc/Hz were obtained at offset frequencies of 1 kHz and 100 kHz, respectively. These results are determined by the phase noise of OSC1, including the optical LDM n-tupler function. Additionally, the values are affected by the spectral purity of the local oscillator OSC2 at 59.5 GHz used for the down conversion and by the SA. The arrow depicts the noise level of the down converter/SA combination.

These experiments demonstrated the good tunability, high millimeter-wave frequency accuracy, and low phase noise of the optically generated millimeter-wave signal. Due to the frequency stability of the temperature stabilized lasers of approximately ± 50 MHz within 1 h, and due to the much wider locking range of the slave lasers, no additional electrooptical PLL's or electrooptical AFC loops were necessary.

V. CONCLUSION

The combination of fiber optics and millimeter-wave techniques offers advantages for pico-cell broad-band mobile communication systems. Additionally to the low-loss transmission and large bandwidth of the fibers, the remote generation of the millimeter-wave signals is a powerful advantage of the optical technique.

In this paper, experiments on generating millimeter-wave signals by optical heterodyning have been investigated applying the multiple and the single optical-source technique. With both methods, millimeter-wave signals depicting frequencies up to 70 GHz have been generated and error-free data transmissions were demonstrated, including transmission via SMF's or via a radio link. When the phase-noise terms of the optical waves were uncorrelated, high transmission bandwidths were required. By mode locking or sideband injection locking, millimeter-wave signals with low phase noise have been obtained so that bandwidth efficient multilevel modulation formats can be used [62].

The most important prerequisite for the implementation of pico-cellular mobile communication systems is the availability of low-cost components. In one of the experiments, it was shown that with respect to expenditure of electronic and optical components, the PIC was superior to the hybrid subsystem. This result shows, as a first example, the potential for cost savings by using monolithic integration of optical and millimeter-wave components.

The ultrafast OMC located in each BS is a further key component. As a first approach, separate chips of photodiodes and amplifiers were combined in hybrid technology, depicting a high responsivity. To get a cost cut for the realization of OMC's, monolithic integration of all components is highly desirable. As a step toward this goal, the monolithically integrated combination of a waveguide p-i-n PD and a traveling-wave amplifier has been built up [14].

In the present state, a final evaluation of the investigated optical millimeter-wave generation techniques may be premature because this paper focused only on the generation techniques. Important parameters have already been addressed, like bandwidth efficiency, phase noise of the generated millimeter-wave signal, and expenditure of electronics and optical components. On the other hand, for the application in distribution or bidirectional communication systems, further parameters have to be considered, e.g., multichannel capability and the possibility of implementing up and down links.

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