Novel Techniques for High-Capacity 60-GHz Fiber-Radio Transmission Systems

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***Abstract*— A broad-band 60-GHz fiber-radio transmission experiment has been performed using a combination of novel techniques. The 60-GHz carrier signal was generated using a master/slave (M/S) distributed-feedback (DFB) laser configuration, which gave high purity and high power with very wide frequency tunability. The data path was separated in the wavelength domain from the carrier path so that a remote upconversion scheme could be used to provide a fully transparent link. An electroabsorption modulator (EAM) was used as a full duplex transceiver so that bidirectional optical transmission could be implemented without the need for a laser at the remote site. Transmission of a 120-Mb/s QPSK signal over a fiber span of 13 km and a radio path of 5 m was demonstrated. Furthermore, the downstream optical signal contained the 120-Mb/s QPSK signal multiplexed with 20 channels of TV. The upstream optical signal consisted of 120-Mb/s QPSK data only. Good error performance was simultaneously achieved in both directions.**

***Index Terms*— Antenna feeds, electro-optic devices, injection-locked oscillators, laser modes, millimeter-wave communication, mobile communication, optical modulation/demodulation.**

I. Introduction

HIGH-CAPACITY wireless networks of the future are likely to use millimeter (mm)-wave radio as the access medium. The bands around 60 GHz have been identified for this purpose; for example, the European Radiocommunications Office has identified two sub-bands for mobile broad-band applications [1]. The first is 62–63 GHz for base to mobile links, and the second is 65–66 GHz for mobile to base links. These bands are especially attractive for high-capacity systems due to the availability of adequate spectrum.

For any wireless network based on mm-wave radio systems to be viable, the cost of the infrastructure must be much lower than is currently the case. One approach that promises this cost reduction is radio-over-fiber [2], where radio signals at the carrier frequency are delivered over an optical network to the radio-access point (RAP). Benefits of this centralized approach are that expensive and delicate pieces of equipment can be located in a benign environment and costs can be shared between a number of RAP's.

Optical fiber is well known as a transmission medium with an enormous bandwidth of about 4 THz for the 1.55-μm wavelength region where erbium-doped fiber amplifiers (EDFA) are most effective. A significant limitation to the exploitation of this bandwidth using an analog subcarrier link is the high-frequency performance of optical source and receiver devices. In particular, direct modulation of laser diodes is restricted to frequencies below the mm-wave band. Several techniques and devices have been developed to address this problem [3]–[11]. One solution, based on optical heterodyning, is presented in this paper. This consists of a master/slave (M/S) distributed feedback (DFB) laser arrangement, where each laser contributes a single mode for optical mixing in a high-speed photodiode [12]. This is described in more detail in Section II-A.

However, imposing the data signal onto the mm-wave carrier generated by such a technique is not straightforward. One method of providing transparency and complete modulation format flexibility for the link is described in Section II-B. The technique uses a separate optical path for the data signal, and the upconversion is performed at the RAP using a conventional electrical mixer.

A novel implementation of the data path photodetector is described in Section II-C. An electroabsorption modulator (EAM) is used in this role, since it can also be used simultaneously for the return path by remodulating the light not absorbed during the photodetection process in a loop-back type of configuration [13]. This architecture can reduce the cost and complexity of the RAP.

These techniques have been combined in an experiment in which QPSK data at 120 Mb/s and 20 channels of satellite TV, together with a 60-GHz carrier signal, were transmitted over 13 km of nondispersion-shifted fiber (NDSF) for remote upconversion and onward radio transmission over a free-space path. This experiment is described in Section III.

II. Techniques

A. M/S DFB Laser Technique

We describe a new technique for the optical generation of mm-wave signals which is simple to implement and gives high power, high purity signals with tunability, and high stability. It uses optical heterodyning of two single-mode lasers to generate a beat signal in a photodiode. The lasers are in a series M/S configuration [14], and very low phase noise is produced in the beat signal simply by subharmonic electrical injection of the slave laser (SL).

The experimental arrangement is shown in Fig. 1. Each laser contributes a single mode; the output of the SL consists of

Manuscript received December 6, 1996; revised April 23, 1997.

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Publisher Item Identifier S 0018-9480(97)05996-6.

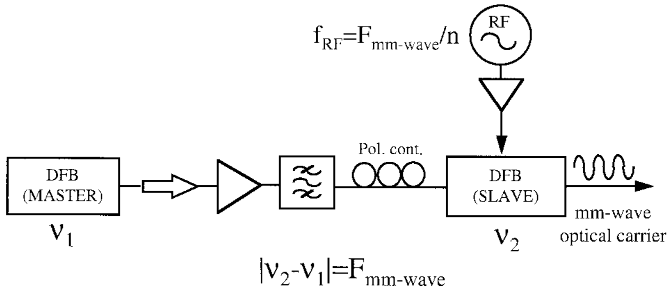


Fig. 1. Experimental arrangement of the subharmonic electrically injection-locked M/S technique.

the slave mode and the mode from the master laser (ML). These modes beat together in a fast photodiode to produce the desired mm-wave signal. Although other less-powerful side modes are also present, their effect is negligible since a narrow-band RF filter is used at the RAP. An electrical drive to the SL at a subharmonic of this beat frequency generates a series of sidebands. The ML mode injection-locks one of these SL sidebands, which results in phase-noise cancellation in the output signal. The purity of the resulting mm-wave signal is then derived from that of the electrical-drive source, which can have sub-hertz linewidth.

For characterization, the ML signal was generated by a tunable laser which allowed fine tuning of the optical frequency. The SL was a DFB laser emitting at 1554 nm with one antireflection-coated facet and mounted in a two-fiber pigtailed package with a 3-dB bandwidth of 14 GHz. The ML signal was coupled into the coated facet of this DFB and the output was taken from the uncoated facet. The ML optical-power level was adjusted to ensure that the output optical power from both modes were equal. The two-moded optical signal from this arrangement was launched into a high-speed edge-coupled p-i-n photodiode. The SL was electrically modulated using an RF synthesizer, and carrier generation at both 50 and 60 GHz was investigated.

The optical and electrical spectra obtained are shown in Fig. 2. The electrical drive to the SL was 21 dBm at 16.66 GHz, although other (lower frequency) subharmonics were also used successfully. The ML optical signal was detuned from the SL mode by +50 GHz with an optical-power level in the fiber of 1.4 mW.

With no electrical drive to the SL, Fig. 2(a) shows the ML and SL modes with a wavelength separation of 0.39 nm, which corresponds to a beat frequency of 50 GHz [shown in Fig. 2(b)]. With the electrical drive applied, the output signal becomes extremely pure [shown in Fig. 2(d)]. A phase noise of −100 dBc/Hz at 100-kHz offset is observed, which represents a degradation of only 10 dB when compared to the signal purity of the synthesizer.

The long term stability of the signal has been quantified by measuring the immunity of the system to the detuning of the ML optical frequency. A comparison with simulation results using a large-signal time-domain traveling-wave laser model [15] was also carried out. As reported in [12], there is excellent agreement between the measurement and the theory. In both cases, a locking range of 2.5 GHz is found.

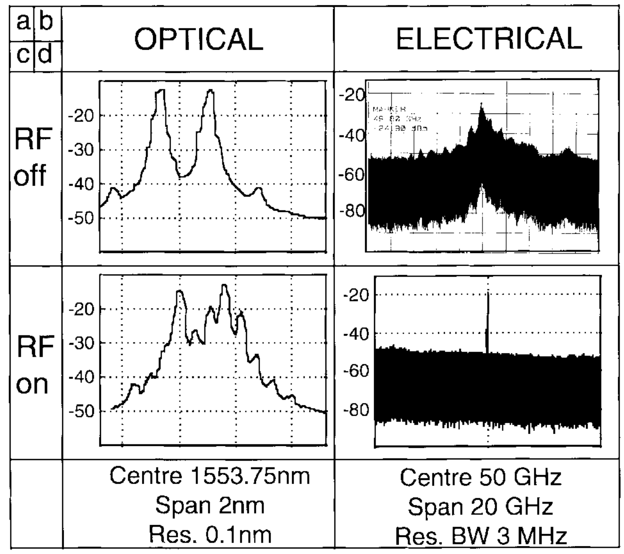
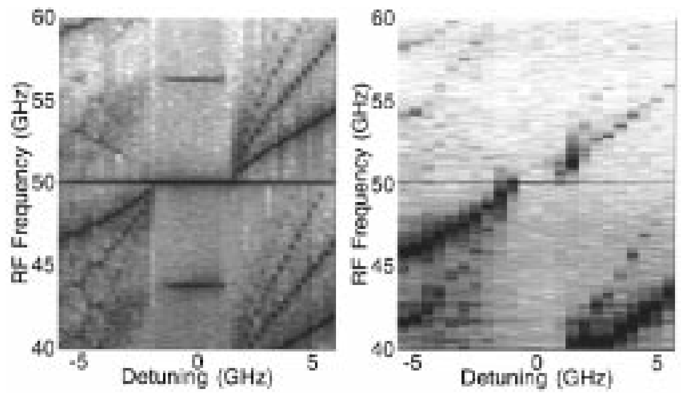


Fig. 2. Optical and electrical spectra, measured with and without subharmonic electrical injection to the SL.



(a) (b)

Fig. 3. Map of electrical spectrum versus detuning of the injected master frequency showing locked and unlocked behaviors achieved by (a) calculation and (b) experiment. Dark shades denote higher powers.

To gain further insight into the locking process, the electrical spectra were measured experimentally and simulated on the computer, as the ML wavelength was detuned in 0.5-GHz steps on either side of the wavelength for optimal locking. These spectra are displayed as a function of detuning in the colormaps [see Fig. 3(a) and (b)]. Several features stand out from these plots. The broad lines at an angle close to 45° show that, in the unlocked state, the RF beat frequency is simply equal to the optical frequency separation of the ML and the SL sidebands. These lines are broad (many megahertz) indicating the broad RF linewidth of the M/S arrangement in the unlocked state. In both plots, other lines which are twice as steep, are visible and are attributed to frequency mixing in the SL. In the simulation results, RF components separated from the 50-GHz main beat frequency by half the 12.5-GHz RF-locking frequency are also observed in the locked state. These are not visible in this experimental plot, but were observed under different conditions, indicating that frequency division can occur. As the ML wavelength is tuned in closer to the locking point (toward the middle of the figures), the angle of the lines gets steeper. This indicates that pulling of the SL wavelength by the ML signal takes place, as is common in conventional injection locking. Finally, in the center of the figure, a stable locking range of about 2 GHz is seen where the RF spectrum does not depend on the injected master wavelength.

The M/S DFB technique is simple to implement and gives pure, stable, and high-power signals that can be tuned to any of the mm-wave radio bands discussed in Section I. Furthermore, because the optical spectrum is substantially two-moded, transmission over long spans of NDSF should not present any problems due to chromatic dispersion [16].

B. Remote Upconversion Technique

Modulation of the mm-wave carrier signal with data is not straightforward in fiber-radio systems for two main reasons. The first concerns the modulation capabilities of the carrier generation scheme. For example, the M/S arrangement described in Section II-A is not amenable to all types of modulation format or to large modulation bandwidth as there is a limited bandwidth over which the optical modes will remain locked. In an ideal system, full transparency to modulation type and bandwidth should be possible. The second problem arises from chromatic dispersion in the optical fiber. The optical system we describe in Section III operates at a wavelength of around 1550 nm to take advantage of the availability of EDFA's, which will compensate for losses from optical splitting. At this wavelength, NDSF has a dispersion coefficient of around 17 ps/nm/km. A system that can work with this dispersion will provide maximum flexibility since there is no need to install special fiber.

At mm-wave frequencies, dispersion can cause significant signal fading even over very short fiber spans (1 km or less) [17]. For the case of carrier generation, a two-moded optical spectrum avoids this problem, since only one beat component is produced in the photodiode. However, if data are mixed with the carrier prior to transmission, then dispersion will cause fading unless the modulation is restricted to only one of the optical modes. This arrangement has been used previously [18], but required splitting and recombining of the optical modes.

A solution to both of these potential problems is to mix the carrier and the data signals at the RAP (i.e., remote upconversion). In the basic form of this technique, a separate laser and photodiode pair are used to transport the data signal to the RAP where it can be combined with the carrier signal using a conventional electrical mixer. A simpler variant of this has been demonstrated using a single heterojunction bipolar phototransistor [19].

A new approach to remote upconversion is used in this paper. The main difference is the use of an EAM at the RAP instead of a photodiode. Furthermore, as discussed in Section II-C, this device can simultaneously act as a modulator for the upstream path.

The carrier and downstream data signals are sent across the optical link on separate wavelengths, possibly using wavelength division multiplexing (WDM) couplers to share a single fiber. At the RAP, these signals are detected, amplified, and mixed to perform the upconversion function prior to radio transmission via a filter, duplexer, and antenna. The upstream radio signal comes in via the antenna, duplexer, and amplifier, and is downconverted using a mixer with the carrier signal from the downstream path. The downconverted signal is input to the EAM transceiver, where it intensity modulates the light from the data laser which was not absorbed during the photodetection process. This signal is then returned to the central office (CO) where it is detected using a photodiode.

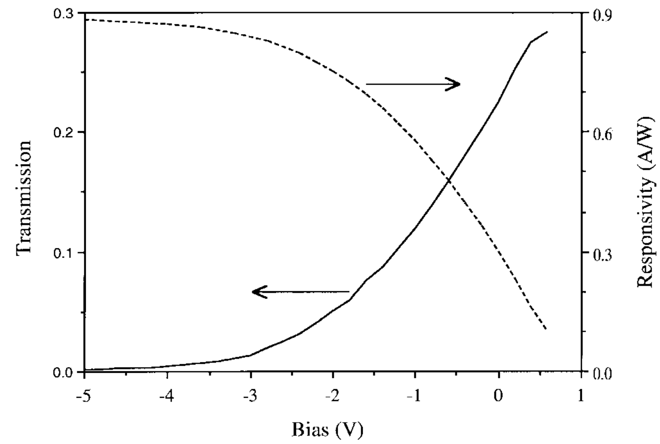


Fig. 4. EAM dc characteristics.

C. EAM Transceiver

It is important to minimize the cost of the RAP in broadband mm-wave fiber-radio systems. The laser and its associated control circuitry account for a significant proportion of the cost of a conventional bidirectional RAP. Bidirectional fiber-optic links in which the remote laser is replaced with an optical intensity modulator in reflecting [20] and loop-back [21] configurations have been demonstrated. However, greater cost savings could be realized if both transmit and receive functions at the RAP were performed by a single component with a low power requirement.

There has recently been considerable interest in the use of EAM's as transmitters in analog fiber-optic systems [22]–[27]. Their low-chirp and low-drive voltages make them attractive for analog modulation provided that their inherent nonlinearity is controlled. It has been shown that an EAM can be used as a photodiode and modulator *alternately* in a *digital* optical system [28]. In this section, we present an overview of recent experiments which for the first time demonstrated the viability of using an EAM as a *simultaneous* transmitter/receiver in a bidirectional *analog* fiber-optic link.

The ridged deeply etched buried-heterostructure EAM used in these experiments was of the type previously described [29]. The transparent state fiber-to-fiber insertion loss at 1550 nm of a 371-μm-long device packaged in a high bandwidth module was only 4.9 dB. Modulation and photodetection 3-dB bandwidths were both $\approx$14 GHz at moderate reverse bias. Fig. 4 shows the measured modulator fiber-to-fiber transmission and responsivity as a function of applied bias for 0 dBm of TE polarized light at 1560 nm.

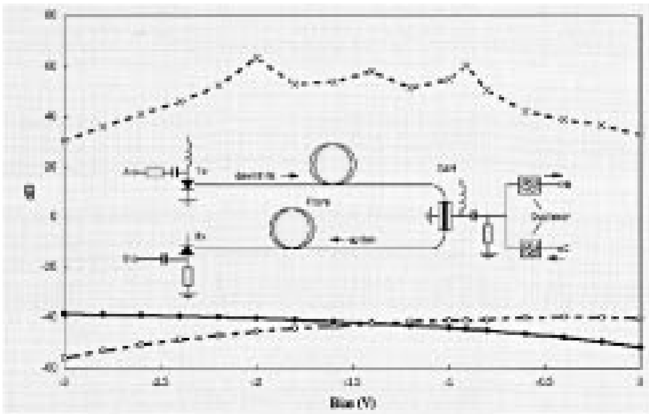


Fig. 5. Downlink RF insertion gain (closed circles/solid curve), uplink gain (open circles/dot–dashed curve), and uplink C/I (crosses/dashed curve), as functions of EAM bias. (Inset: experimental layout.)

We recently proposed and demonstrated the feasibility of using an EAM as a full duplex transceiver [13] in the narrow-band (sub-octave) bidirectional analog fiber-optic link shown in Fig. 5 (inset). In that experiment, the downlink transmitter was a commercial DFB laser, emitting +6 dBm into the fiber at 1560 nm. RF insertion losses, measured at 1.0 GHz, are shown in Fig. 5 for both downlink ($A - B$) and uplink ($C - D$), as functions of modulator bias. These losses were made equal (≈42 dB in a 50-Ω system) at a bias of −1.4 V. By way of comparison, the insertion loss of our commercial laser and detector modules (no modulator) was 39 dB.

Intermodulation distortion is a significant problem in analog optical links due to the generation of spurious frequency components. The uplink carrier to third-order intermodulation ratio (C/I) measured at the receiver (D) with two 0-dBm RF tones (913.5 ± 0.1 MHz) applied to the modulator (C) is plotted in Fig. 5 as a function of bias voltage. A number of C/I maxima (≈ 60 dB) were observed.

For narrow-band links we observed that intermodulation in the uplink was generally more significant than uplink–downlink mixing (via the modulator characteristic). When a second pair of 0-dBm tones (958.5 ± 0.1 MHz) were simultaneously applied to the laser (A), and the EAM bias was optimized purely for minimum uplink distortion (−2.0 V), the downlink C/I was ≈ 50 dB. In some picocellular architectures, a more realistic uplink input power would be <−10 dBm, which gave a downlink C/I of >65 dB, limited by the linearity of our laser transmitter.

This technique was used to provide broad-band bidirectional data links in a subsequent experiment [30] in which full duplex analog transmission of 120-Mb/s QPSK data was performed over 25 km of NDSF using a loop-back configuration similar to that shown in Fig. 5 (inset). A QPSK modem signal, upconverted to 1.35 GHz, was applied to a commercial analog DFB laser module, which emitted an optical power of +6 dBm at 1560 nm. After transmission over 25 km of NDSF, the optical signal was detected in the remote EAM transceiver. A further 120-Mb/s QPSK modem signal, centered at 140 MHz, was applied to the modulator via a duplexer/multiplexer and impressed on the optical signal for the return path to a receiver module.

With RF powers set to 0 dBm and the EAM bias set for minimum third-order intermodulation in the uplink ($V_b = -0.98$ V) we observed no power penalty associated with the use of an analog EAM transceiver in this full duplex system. The minimum received optical powers for a bit-error rate (BER) of 10^{-8} were −27 and −20 dBm in the uplink and downlink, respectively.

These experiments show that RF insertion losses of the EAM transceiver are comparable with those of a conventional laser-detector arrangement and that intermodulation between transmit and receive signals can be maintained at an acceptable level.

The cost of this bidirectional analog-transmission scheme could be further minimized by addressing the cost of the EAM module itself. Reductions in the cost of a packaged optoelectronic component can be achieved by using a passive fiber-alignment strategy [31]. This approach could be used to produce low-cost/high-performance EAM modules suitable for widespread use in analog transmission systems.

III. Transmission Experiment

A. System Overview

Here we present an experimental fiber-radio system which combines all of the above techniques. The system incorporates the mm-wave optical source described in Section II-A to produce a carrier at 60 GHz. The remote upconversion scheme outlined in Section II-B is used to impose data onto this carrier signal. A simple RAP is constructed using an EAM transceiver as described in Section II-C. The EAM is used to receive 120 Mb/s of QPSK data and 20 satellite-TV channels from the CO and simultaneously to transmit 120 Mb/s of QPSK data back upstream. The 120-Mb/s data received by the EAM was fed to a 60-GHz radio drop and transmitted to a mobile terminal (MT). The TV channels were separated from the data to demonstrate a high functionality node which is, for example, able to act as a feeder for a neighborhood cable-TV system.

B. Experimental Setup

The optical link is illustrated in Fig. 6. We used a pair of 1558-nm DFB lasers (master and slave) to produce a 59.5-GHz signal. To phase lock the modes, the SL was modulated at 11.9 GHz (fifth subharmonic) with 14.7 dBm of drive power. The output of the SL was fed to EDFA 1 to compensate for the loss of both the WDM couplers and of the 13 km of NDSF.

For the downstream data, a 120-Mb/s [$2^{10} - 1$ pseudo-random bit sequence (PRBS)] QPSK signal was upconverted to 1.35 GHz and combined with the downconverted satellite-TV signal from one polarization of an Astra satellite transmission. This electrical signal was applied to a 1537-nm DFB laser. EDFA 2 was used to amplify the resultant optical signal to +5.5 dBm prior to multiplexing it (using a WDM coupler) with the mm-wave signal and transmitting over the fiber. At the RAP, the two optical signals were separated in another WDM coupler. The signal from the M/S laser was detected at the RAP by the broad-band photodetector (photocurrent = 0.43 mA) and the resulting beat signal was used for upconversion of

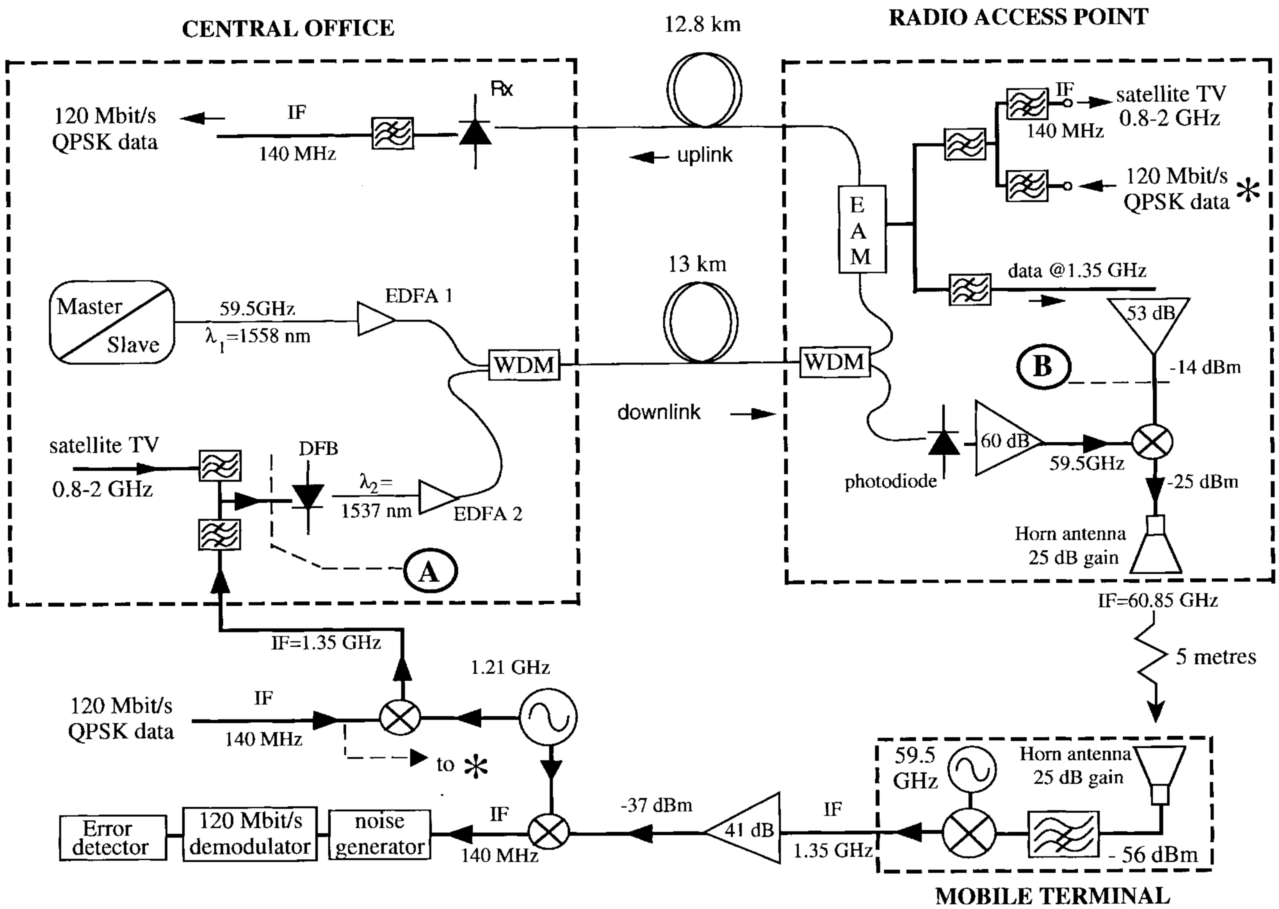


Fig. 6. Layout of 60-GHz fiber-radio transmission system.

the data in the RAP using a mm-wave mixer. The downstream signal was detected in an EAM and the QPSK data was separated from the TV channels prior to upconversion and radio transmission to the MT.

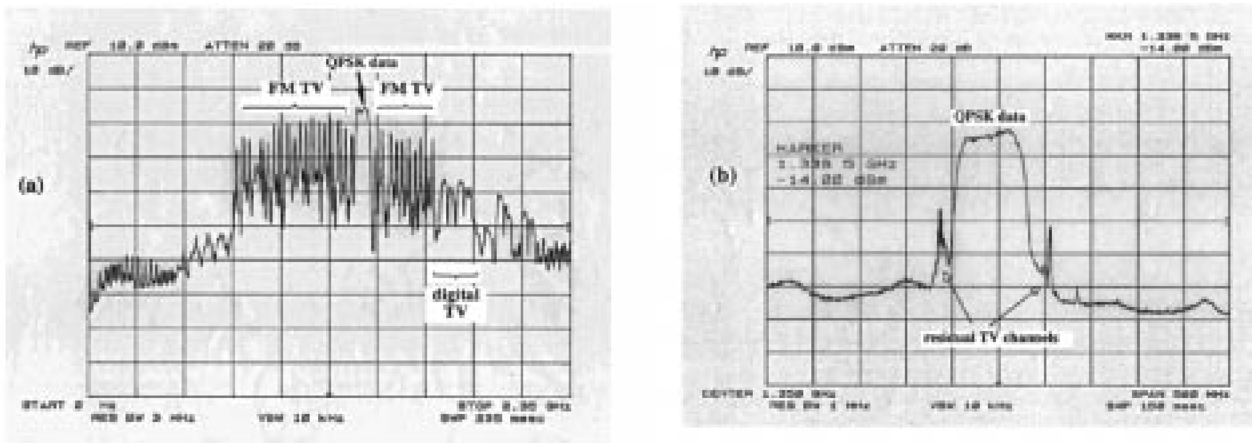
An upstream 120-Mb/s data channel centered at 140 MHz, was simultaneously applied to the EAM via a duplexer/multiplexer, and impressed on the looped-back optical signal. The RF multiplexers gave >80 dB rejection of the uplink signal in the downlink path. The EAM bias was −3.67 V, corresponding to the best compromise for simultaneous photodetection and modulation under these conditions. The upstream signal was detected at the CO by an 8-GHz bandwidth photodetector.

The following two configurations for the radio path transmitter were used: a line-of-sight 25-dB-gain horn antenna and a 1-dB-gain omnidirectional antenna. The received QPSK signal at the RAP (−67 dBm) was amplified to −14 dBm/−5 dBm, respectively, depending on the antenna (horn/omnidirectional) and was upconverted to 60.85 GHz using a mm-wave mixer and the 59.5-GHz signal from the CO (conversion loss of 11 dB). The resulting −25/−16 dBm signal was fed to the respective antenna. The MT used a 25-dB-gain horn antenna. When transmitting using the omnidirectional antenna, the propagation was performed over 1.5 m (70-dB net loss). The transmission with the horn antenna was limited by the size of the laboratory to 5 m (net loss of 81 dB). The available power after downconversion at the MT was −78/−82 dBm, respectively. To assess the complete link performance, a noise and interference test set was used to measure BER versus E_b/N_0 (bit energy/noise). During these measurements, a constant signal level of −37 dBm was maintained into the QPSK demodulator as its performance was power dependent.

C. Results

Fig. 7(a) shows the RF spectrum applied to the laser transmitter (point A in Fig. 6), i.e., TV and 120-Mb/s QPSK data. Fig. 7(b) shows the received QPSK data channel prior to 60 GHz upconversion and radio transmission (point B in Fig. 6).

In Fig. 8, we plot the measured BER at different stages of the link. The back-to-back measurement was performed using the output of the first upconverter at 1.35 GHz and feeding it directly to the downconverter. There was a 1-dB penalty at 10^{-7} BER on the received QPSK signal at the output of the EAM. This penalty is thought to be due to the nonoptimal bandwidth of the demultiplexer causing some shaping of the QPSK data spectrum [see Fig. 7(b)]. For the uplink (data centered at 140 MHz) there was a minimal 0.25-dB power penalty. The insertion loss of the RAP-MT link added a small penalty using the horn antenna, whereas the omnidirectional antenna lead to a further 0.7-dB penalty at 10^{-7} BER. The latter penalty is believed to be due to multipath propagation in the laboratory. Despite this, BER measurements better than



(a) (b)

Fig. 7. Electrical spectra showing (a) transmitted downstream 120-Mb/s QPSK data signal multiplexed with Astra satellite-TV channels and (b) received downstream QPSK data signal after detection in EAM and filtering.

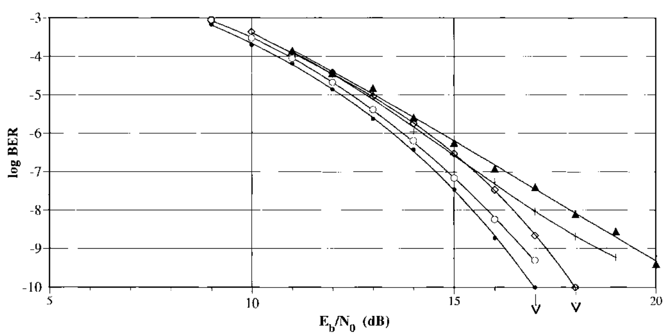


Fig. 8. BER versus E_b/N_0 at various stages of the fiber-radio system. •: back-to-back, ◇: 13-km CO-RAP link at output of EAM, ▲: CO-RAP link and 60-GHz RAP-MT link (omnidirectional antenna), +: CO_RAP link and 60-GHz RAP-MT link (horn antenna), and ○: 12.8-km RAP-CO uplink.

10^{-9} were achieved in all cases. Additionally, no significant degradation of the TV signals received at the RAP could be observed on our TV monitor. The presence of reflections was confirmed when the TV channels were transmitted instead of data and these could be received satisfactorily by the MT without using line-of-sight conditions.

IV. Conclusion

High-quality transmission has been demonstrated in a fiber-radio experiment at 60 GHz using a number of novel techniques. We have shown that a simple M/S DFB laser arrangement is capable of generating high-power and high-purity carrier signals over a wide frequency range with excellent stability. 60-GHz signals with a single-sideband phase noise of only −100 dBc/Hz at 100-kHz offset were generated using this technique. This level of purity is to the authors' knowledge, the best reported figure for an optically generated mm-wave signal.

A transparent data path was provided using a remote upconversion scheme, which was used to avoid potential problems due to chromatic dispersion in the fiber and also modulation limitations imposed by the carrier source.

An EAM was used as the photodiode for the data path, and also as a modulator to provide a return path for the data, thereby removing the need for a laser at the remote site. This device was shown to be capable of full duplex operation as a transceiver.

These novel techniques were combined in a fiber-radio experiment with a fiber span of 13 km and a radio path of 5 m. The signal consisted of a 120-Mbytes/s QPSK data and 20 channels of TV for the downstream path, and a 120-Mbytes/s QPSK signal for the upstream path. Good error performance was simultaneously achieved in both directions for a downstream path that included a radio drop and for a fiber-only upstream path.

We have reported the first demonstration of a high-capacity 60-GHz fiber-radio system which incorporates an attractive strategy for the return path. The novel techniques used in this system are promising in terms of cost and practicality for widespread deployment in future broad-band wireless systems.

Acknowledgment

The authors would like to thank the following people at BT Laboratories, Suffolk, U.K., for their assistance in the course of this work: P. Sully, J. Reed, F. Friend, B. Nigeon, A. Pote, M. Fitch, A. Vobe, H. Rhodes, I. Rose, and M. Goodrum. They would also like to thank S. Gittins of BT Goonhilly earth station, U.K., and M. Roberts of Leeds University, Leeds, U.K.

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