60 GHz radio-over-fiber technologies for broadband wireless services
[Invited]

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Some of the work carried out within the European integrated project Integrated Photonic mm-Wave Functions for Broadband Connectivity (IPHOBAC) on the development of photonic components and radio-over-fiber technologies for broadband wireless communication is reviewed. In detail, 60 GHz outdoor radio systems for >10 Gbits/s and 60 GHz indoor wireless systems offering >1 Gbit/s wireless transmission speeds are reported. The wireless transmission of uncompressed high-definition TV signals using the 60 GHz band is also demonstrated. © 2009 Optical Society of America

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1. Introduction
The past few years have witnessed the emergence of several new bandwidth-hungry multimedia applications such as high-definition TV (HDTV), which is a driving force behind recent endeavors developing very-high-speed wireless communication systems. Although conventional wireless local-area network (WLAN) systems (IEEE 802.11a,b, and g) offer data rates theoretically of up to 54 Mbits/s, more modern alternatives such as ultrawideband (UWB) and multiple input, multiple output (MIMO) systems are able to extend the wireless data speed up to several hundred megabits per second, targeting 1 Gbit/s per user in the near future. However, even this speed is not sufficient for live broadcasting of HDTV signals since just a single uncompressed HDTV (1080i) stream already requires a data rate of about 1.5 Gbits/s. A solution to this bottleneck is seen in the development of wireless systems operating at much higher carrier frequencies in the millimeter-wave (mm-wave) range where more bandwidth is available. Especially around 60 GHz, a bandwidth of about 7 GHz is allocated for wireless communications, 57–64 GHz in North America and South Korea and 59–66 GHz in Japan, and the European Union is currently in the process of creating similar allocations. Consequently, broadband wireless systems operating at around 60 GHz are currently being studied worldwide, e.g., in the IEEE 802.15.3c group focusing on short-range (path length up to 10 m) mm-wave indoor wireless systems for the provision of more than 1 Gbit/s. Even the introduction of 10 Gbits/s Ethernet (10 GbE) wireless standards is expected, supporting the convergence of wired and wireless systems in the access and thus ensuring a suitable mobile telephony network backhauling function in the near future. Further applications are seen in storage area networks (SANs).

Especially for long-range fixed wireless access (FWA) applications, other mm-wave bands such as the E-band (60–90 GHz) or the F-band (90–140 GHz) are considered because those bands offer lower atmospheric gaseous losses. Nevertheless, the potential of 60 GHz for medium-range broadband wireless transmission has not been fully
exploited yet, but the rising interest in 60 GHz technology has already led to higher component availability and lower component cost. Also, future 60 GHz radio-frequency complementary metal-oxide semiconductor (RF-CMOS) technology implies further cost reductions. Altogether, this justifies scenarios using the 60 GHz band for medium-range outdoor wireless point-to-point (p2p) transmission offering speeds >10 Gbits/s as well as for >1 Gbit/s indoor short-reach radio systems.

With the objective of developing microwave photonic components and integration technologies for broadband millimeter-wave wireless systems, 11 European partners have initiated a joint European project entitled Integrated Photonic mm-Wave Functions for Broadband Connectivity (IPHOBAC) [1]. This paper will report on the progress in broadband radio communication systems based on the utilization of advanced microwave photonic components and radio-over-fiber (RoF) technologies achieved in the IPHOBAC project. One of the targeted applications is the provision of very-high-speed point-to-point radio links operating in the 60 GHz frequency band for future mobile network backhauling or high-speed WLAN bridging [2–4]. A second application is the provision of more than 1 Gbit/s short-reach radio communication systems [5–7] such as the one studied in the IEEE802.15.3c working group [8], capable, e.g., of broadcasting uncompressed HDTV signals. In Section 2 of this paper, we will at first report on key photonic components such as 60 GHz mode-locked-laser diodes (MLLDs) [9–16] and 100 GHz photodetectors [17–19] that were developed in the IPHOBAC project especially for broadband wireless applications. In Section 3, we report on 60 GHz short- to medium-range fixed wireless outdoor systems using optical on–off-keying (OOK) modulation and we demonstrate an ultrabroadband radio system offering data speeds of up to 12.5 Gbits/s [2,4]. Based on the experimental achievements and further theoretical calculations we predict maximum path lengths up to the kilometer range for 10 Gbits/s wireless transmission at 60 GHz [20]. We furthermore discuss advanced photonic vector modulation techniques [21,22] required for high spectral efficiency and present experimental demonstration of 10 Gbits/s 60 GHz carriers modulated by 4-quadrature amplitude modulation/quadrature phase-shift keying (4-QAM/QPSK). In Section 4, we report on the provision of a photonic-assisted radio transmission system for indoor applications distributing and delivering throughout a building a UWB 60 GHz radio signal carrying 3 Gbits/s [5,6]. Finally, we report on a compact photonic 60 GHz RoF wireless link demonstrator for transmitting uncompressed high-definition video/audio (HD V/A) signals.

2. Millimeter-Wave Photonic Technologies

Within the IPHOBAC project a number of different types of lasers, photodetectors, modulators, and transceivers are being developed for applications not only in broadband wireless communications but also in instrumentation and radar/sensor applications [1]. In the following subsections, key components required for broadband wireless systems developed in the IPHOBAC project will be presented. In detail, 60 GHz band 1.55 μm mode-locked Fabry–Perot (FP) lasers utilizing a quantum-dash (QD) active material and the development of ultrabroadband (>100 GHz) 1.55 μm waveguide photodetectors are reported.

2A. 60 GHz Band Mode-Locked Quantum-Dash Fabry–Perot Lasers

Mode-locked laser sources are very attractive solutions for various applications such as pulse generation, clock extraction from digital data, and optical microwave signal generation and processing [8]. Previously published work showed how FP QD mode-locked lasers could be used to achieve low-phase-noise oscillators at 39.8 GHz [10]. To achieve devices adapted for 60 GHz wireless transmission, mode-locked lasers oscillating within this frequency range have been specifically fabricated for direct generation of the millimeter-wave tone without any external reference oscillator. The linewidth of the tone is expected to be sufficiently narrow to be used as a carrier for wireless transmissions. In addition, the ability to perform direct modulation of the laser can be used to modulate the transmitted data on the carrier using the same device, avoiding the need for an additional external modulator.

The studied semiconductor lasers are made of a buried ridge structure and contain an active layer based on QDs on an InP substrate. The vertical structure is described in a previously published work [10]. Both facets are cleaved, forming a 774 μm long
FP cavity. The QD FP laser was mounted on an AlN carrier with a ground-signal-ground (GSG) coplanar guide for biasing and direct modulation.

Passive-phase-modulation-type mode-locking has been obtained with these devices without the use of any specific saturable absorber. Figure 1 shows an example of the beating spectrum observed at a DC bias current of 370 mA, with the resolution bandwidth of the electrical spectrum analyzer (ESA) set to 3 kHz. One can observe a self-pulsation frequency close to 54.8 GHz, corresponding to the inverse of the round-trip time of the optical wave in the cavity. A nearly Lorentzian line shape is obtained, exhibiting a $\sim 3$ dB linewidth narrower than 18 kHz. A Lorentzian fit is also shown in the figure. The extremely narrow linewidth for QD lasers is believed to be a consequence of the reduced spontaneous emission rate coupled with the lasing mode and sufficient four-wave mixing in these QD structures [11].

The electrical power that is obtained from a mode-locked laser source depends on the beating between the optical modes during the photodetection process. The signal obtained after photodetection will be composed of the sum of all the beating signals corresponding to the frequency of interest in phase and amplitude. The highest millimeter-wave power will be obtained if the relative phase difference between the adjacent modes is the same. Thus, the RF signal will be even more sensitive to the phase dispersion because the number of optical modes is large. There are two main contributions to the relative phase: the dispersion in the laser itself and the dispersion associated with the optical fiber used for the transport of the optical signal. Optimizing the transmission efficiency will require these two contributions to be minimized. Studies of the phase dispersion of mode-locked lasers have shown that with semiconductor lasers the dispersion has a strong linear part [12–14]. This dispersion was shown to be compensated using standard single-mode fiber, enabling subpicosecond pulses to be achieved [13–16]. Improving the electrical power available at the fundamental frequency of a mode-locked laser requires the same conditions as those needed to reduce the width of a pulse. Minimizing the dispersion between the different beat notes will also increase the amplitude at the corresponding frequency. We have measured the electrical power after photodetection from the mode-locked laser. The laser was biased at 370 mA. At this bias level the coupled optical power was 11 mW. Detection was made using the commercial XPDV2020R 50 GHz photodiode (PD) from u2t. The electrical power at 58.4 GHz was measured using an Agilent E4448A ESA coupled to a V-band (50–75 GHz) H-P 11974V preselected harmonic mixer. The measurements were performed after propagation through different lengths of standard single-mode fiber. Figure 2 presents the results of these measurements (diamonds) with a correction used to remove the contribution of the coupling losses associated with the numerous sections of fiber that had to be used. This was done by a normalization using the values of the measured DC photocurrents. Without correction, the electrical power was $-19.7$ dBm when measuring directly at the output of the laser and was improved to $-6.8$ dBm for a fiber length of 50 m and $-15$ dBm for a fiber length of 2370 m.

The theoretical variation can be calculated by assuming a linear dispersion from both the laser itself and the fiber. Experimentally, a dispersion of $-1.2$ ps/nm was found for the laser itself. The calculated results are shown in Fig. 2. In the calcula-

![Fig. 1. Self-pulsation electrical spectrum at 370 mA.](image-url)
tion, the relative power of the different modes of the optical spectrum needed for the model was taken from the spectrum of Fig. 1, and a dispersion of the fiber of 17.8 ps/nm/km is used. The agreement between the measured and the calculated data is good, showing that in the laser linear dispersion is dominant. Thus, this part of the dispersion can be compensated using the appropriate length of standard single-mode fiber.

From these measurements it can be observed that an improvement of the electrical power of more than 15 dB compared with the laser alone can be obtained just by using 65 m of standard single-mode optical fiber. It is important to note that the optimum fiber length ranges are narrow. The length of the optical fiber must be precisely adjusted in order to achieve efficient power generation.

The shapes of the pulses have been measured for the different fiber lengths using an autocorrelator. Figure 3 presents one of the traces obtained after propagation through 65 m of single-mode fiber. The measured pulse had a FWHM of 722 fs, resulting in 480.5 fs after deconvolution, assuming a sech² shape.

2.B. 100 GHz Broadband and High-Output-Power Photodiodes
Advanced broadband photodiodes are key components for several mm-wave applications in broadband wireless, radar/sensing, and instrumentation. A key challenge in that regard is the development of ultrawideband photodiodes capable of high-output-power millimeter-wave signal generation. In IPHOBAC, various types of high-output-power PDs are developed. This includes evanescent coupled pin waveguide PDs [17], waveguide-coupled uni-traveling-carrier (UTC) PDs [18], as well as partially doped partially nonabsorbent traveling-wave (TW) PDs [19]. Also, for enabling system-level demonstrations such as optical mm-wave generation, we have developed a small form factor fiber-optic package with a hermetic housing and a coaxial RF output connector.
The general concept of the developed housing is based on a PD package with a V-connector for operation up to 50 GHz. Based on this concept, a package with a w1 connector (1 mm) has been developed and is shown in the photo of Fig. 4. Here, a critical point is the RF connection from the photodetector chip to the outer coaxial connector, which must be very broadband, highly efficient, low loss, and without resonances. A specially designed grounded coplanar wave (CPW) substrate acts as the connecting part between the photodetector chip and the coaxial connector. The measured frequency response of the packaged devices is shown in Fig. 4 (right). As can be seen from this figure the packaged devices exhibit a 3 dB cutoff frequency at around 100 GHz. The total frequency roll-off from DC to 110 GHz is approximately 5 dB.

3. 60 GHz RoF System for up to 12.5 Gbits/s Wireless Access

3.A. 60 GHz RoF System Setup
In this section, we report on the development of a RoF system offering data rates >10 Gbit/s that would potentially allow transmission of 10 Gbit Ethernet signals for future mobile network backhauling or high-speed WLAN bridging. Figure 5 shows the system configuration of the developed radio-over-fiber link. It consists of a 60 GHz optical carrier generation unit followed by a broadband optical data modulation, a wireless RoF transmitter making use of the broadband photodiode, as well as a wireless 60 GHz receiver.

For generating the optical 60 GHz carrier signal, light from a 1.55 μm external-cavity laser is modulated by a single-drive Mach–Zehnder modulator (MZM-1). The bias of MZM-1 is set to the minimum transmission point for generating an optical double-sideband signal with a suppressed carrier (DSB-SC). Hence, the frequency of the driving local oscillator (LO) is half of the required wireless RF frequency, i.e., \( f_{\text{LO}} = 30 \text{ GHz} \). The generated optical mm-wave signal is then coupled to a second Mach–Zehnder modulator (MZM-2), biased to the quadrature point and modulated by non-return-to-zero OOK (NRZ-OOK) data. For our experiments, we used a pseudorandom binary sequence with a word length of \( 2^{31} - 1 \) and data rates of up to 12.5 Gbits/s. An optical bandpass filter is used to remove amplified spontaneous emission (ASE) noise from the erbium-doped fiber amplifier (EDFA) and an optical attenuator is used to control the optical power. After fiber-optic transmission the signal is detected using a broadband photodiode described in Section 2, amplified up to approximately +11 dBm and transmitted using a standard horn antenna with 20 dBi gain. The wireless 60 GHz signal is detected in the wireless receiver unit using an identical 20 dBi horn antenna and it is further amplified by a low-noise amplifier (LNA). Finally, the received 60 GHz signal is downconverted directly to baseband using a low-loss custom-design balanced mixer and an amplifier for performing bit error rate (BER) measurements.

3.B. Broadband Short-Range Indoor Experiments
At first, we investigated the performance of the constructed RoF system described above within a laboratory indoor environment allowing a maximum wireless path length of approximately 11 m. For the indoor measurements, no amplifier was used in the wireless RoF transmitter, but the 60 GHz signal was transmitted directly after optical/electrical (o/e) conversion. At first, BER measurements were carried out for a wireless path length of 2.5 m at various data rates of 5, 7.5, 10, and 12.5 Gbits/s. As
can be seen from Fig. 6, no error floor was observed even for BERs of $10^{-11}$. For a BER of $10^{-9}$ ($2^{31}-1$, NRZ) the measured receiver sensitivities at 5, 7.5, 10, and 12.5 Gbits/s were $-51.8$, $-50.1$, $-47.6$, and $-45.4$ dBm, respectively. Thus the receiver sensitivity is reduced by approximately 2 dB when the data rate is increased by 2.5 Gbits/s. We also verified the maximum wireless path length the system could accommodate without using any RF amplification in the wireless transmitter unit for a fixed safe optical input power to the PD of +10 dBm. Under these conditions, the maximum wireless path length achievable for a 10 Gbits/s signal were approximately 8.5 and 5 m for BERs of $10^{-4}$ and $10^{-9}$, respectively.

3.C. Broadband Medium-Range Outdoor Experiments
For studying the system's performance for medium-range broadband mm-wave wireless transmission, outdoor experiments were carried out on the university's campus.

Fig. 6. Measured bit error rates with respect to the power of the received 60 GHz band wireless signal. Data shown represents the measured BER for 5, 7.5, 10, and 12.5 Gbits/s after wireless transmission over 2.5 m.
Figure 7 shows a photo of the setup with the constructed 60 GHz RoF wireless transmitter in the front and the 60 GHz wireless receiver located at a distance of up to 40 m. The measurements were carried out under fair weather conditions, as can be seen from Fig. 7. The system setup was surrounded by buildings, limiting the maximum wireless path length to 40 m, and the height over ground was only about 120 cm. No precautions were taken to avoid multipath propagation, e.g., due to ground reflections. The outdoor experiments were performed at data rates of 5, 7.5, 10.3125 (gross data rate required for 64/66 coded 10 Gbit Ethernet), and 12.5 Gbits/s (gross data rate required for 8/10 coded 10 Gbit Ethernet).

Figure 8 shows the BER characteristics after 20 and 40 m wireless transmission. From the results, a sensitivity of $-46$ dBm for error-free ($\text{BER} < 10^{-9}$) transmission of 10.3125 Gbits/s is observed. The sensitivity for 10.3125 Gbits/s operation after 40 m wireless path length is slightly better than for 20 m, which is attributed to reflections from buildings. As can be seen from Fig. 8, the maximum data rate of 12.5 Gbits/s was achieved for 20 m wireless transmission. However, error rates were limited to approximately $5 \times 10^{-7}$ in this case. This can be traced back solely to the power link budget limitation because the indoor experiments reported above have clearly revealed that there is no error floor even for 12.5 Gbits/s. Thus we expect that error-free transmission of 12.5 Gbits/s is achieved when using either a slightly larger RF gain or antennas with a higher directivity. We furthermore generally expect an improved receiver sensitivity due to reduced multipath propagation by placing the wireless transmitter and receiver at a higher position over ground, e.g., on the roofs of two buildings.

3.D. Wireless Range Extension to the Kilometer Range

Based on the above-mentioned experiments, we further investigated the potential for wireless range extension to the kilometer range by using high-gain antennas such as 50 dBi Cassegrain antennas [23]. Although higher mm-wave frequencies in the E- and F-bands offer lower gaseous attenuation, the investigated 60 GHz system is expected to allow wireless distances up to the kilometer range, even when considering heavy rain fall. Figure 9 shows the most significant contributions to the total wireless path loss for a 1 km long air transmission within the V-band. Although gaseous losses peak at around 60 GHz due to oxygen absorption, the free-space path loss (FSPL) is clearly the dominating contribution to the total loss within the V-band with a loss figure of

Fig. 7. Photo of the broadband outdoor fixed wireless access experiments showing the 60 GHz wireless transmitter and receiver. The experiments were carried out 120 cm above ground and were surrounded by buildings. Maximum wireless line-of-sight distance was environmentally limited to 40 m.
more than 100 dB. Also, rain attenuation can be neglected against the FSPL. Considering further that the FSPL rises with the square of the carrier frequency, this result shows that for medium path lengths up to the kilometer range the 60 GHz band is still favorable as compared with wireless systems operating at higher carrier frequencies such as 77, 120, and 300 GHz. This is true although oxygen absorption peaks at 60 GHz.

The results presented in Fig. 9 are theoretically determined based on the model from van Vleck, Liege, and Blake for gaseous attenuation as well as from Olson and Rogers for rain attenuation [24]. Rain amount data from a middle-European country was taken from [25].

To study the capability of the developed system for wireless path extension up to the kilometer range we have calculated the power received by the wireless receiver as a function of wireless length. For this study, the 60 GHz free-space propagation loss and a maximum gaseous attenuation of 15.5 dB/km were considered. Also, to study the link availability with respect to weather conditions, different rain attenuation figures based on sample rain data from a middle European country were considered. In detail, the rain attenuation figures used for a link availability of 99%, 99.99%, and 99.999% are 1.3, 10.1, and 32.5 dB/km, respectively [24,25]. Figure 10 shows the received power versus wireless path length in case 50 dBi gain antennas are used. The corresponding receiver sensitivities for achieving a BER of $10^{-9}$ for data rates of 10.3125 Gbits/s (gross data rate required for 10 Gbit Ethernet transmission using 64/66 coding) and 12.5 Gbits/s (gross data rate required for 10 Gbit Ethernet transmission using 8/10 coding) are also indicated by the dashed lines.

![Figure 8](image1.png)

**Fig. 8.** Measured bit error rates as a function of received power of the 60 GHz band wireless signal. BERs are shown for 5, 7.5, 10.3125, and 12.5 Gbits/s for wireless path lengths of 20 and 40 m.

![Figure 9](image2.png)

**Fig. 9.** V-band FSPL, gaseous loss, and rain attenuation (25 mm/h) as well as total path loss after 1 km wireless transmission over air.
As can be seen from Fig. 10, the maximum wireless distances for a 10 Gbits/s signal (BER=10\(^{-9}\)) ensuring link availabilities of 99.999%, 99.99%, and 99% are 600, 1100, and 1500 m, respectively.

### 3.E. Fiber-Optic Range

In general, optical mm-wave double-sideband (DSB) transmission over fiber leads to severe effects of chromatic dispersion assuming a dispersion coefficient of \(D=17\) ps/nm/km at 1550 nm for standard single-mode fiber. The power fading due to phase shift between the upper and lower optical sidebands may result in destructive interference of the beating products (each sideband with the optical carrier) during o/e conversion, depending on the fiber length, thus significantly reducing the received power [26]. Considering an eye diagram, this would cause a vertical closure of the eye. In our system we have an optical carrier suppression of 26 dB; i.e., we are using an optical carrier-suppressed double-sideband signal, and thus the power penalty due to power fading is severely reduced.

A second effect is the phase shift of the data within the upper and lower optical sideband during o/e conversion corresponding to a horizontal eye closure [27]. Here, the data rate (i.e., the bit period) determines how much phase shift is tolerable. Figure 11 shows the relationship between the data rate and the maximum allowable fiber length for causing a dispersion-induced power penalty (DIPP) due to data phase shift of 3 dB [28].

As can be seen from Fig. 11, a fiber length of approximately 3 km causes a 3 dB DIPP for a 10 Gbits/s signal.

### 3.F. Photonic Vector Modulation

In this subsection, the technique of photonic vector modulation for generating spectrally efficient modulation formats is described. Using photonic vector modulation, millimeter-wave wireless links with various advanced modulation formats such as

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**Fig. 10.** Received power as a function of wireless path length when using highly directive antennas with an antenna gain of 50 dBi. Dashed lines represent the 60 GHz wireless receiver sensitivities for 10.3125 and 12.5 Gbits/s.

**Fig. 11.** Fiber length causing a 3 dB power penalty due to phase shift of the data signal versus data rate for DSB-SC modulation.
QPSK, 16-QAM can be generated, and up to 10 Gbits/s 16-QAM-modulated millimeter-wave carrier generation is demonstrated [21]. In the photonic vector modulator, two DFB lasers at 1554.14 and 1558.17 nm wavelengths, with a modulation bandwidth of 4 GHz are directly modulated by two (I and Q) 5 Gbits/s 27−1 PRBS data streams, respectively. Figure 12 shows the schematic of the experimental setup.

The optical carriers with the I and Q data modulated in a NRZ-OOK format are individually modulated by an electrical carrier of \( f_{\text{LO}}/2 = 30 \) GHz using two 45 GHz Mach–Zehnder modulators biased at the minimum transmission point. The bias of the MZM is chosen such that an optical carrier suppression (OCS) modulation is generated, and harmonics separated at 60 GHz are generated. The Q-arm optical signal is now delayed by \( f_{\text{LO}}/4 \), which corresponds to a 90° phase shift between the I and Q electrical carriers. The two optical signals are combined using a 3 dB coupler and photodetected using a 100 GHz photodetector with a responsivity of 0.5 A/W. The input power to the photodetector was measured as −14 dBm.

The photodetector output is a 10 Gbits/s 4-QAM-modulated 60 GHz carrier. Based on the photodetector input optical power and the responsivity, the output RF power was calculated as −48 dBm. The 10 Gbits/s 4-QAM signal was amplified using a LNA with a gain of 16 dB. The RF signal was later filtered using a bandpass filter with a bandwidth of 10 GHz. Another high-power amplifier (HPA) with a gain of 27 dB was used to amplify the signal further. To emulate the effect of wireless transmission, 50 dB attenuation was added, which can be translated into a distance of 40 m if antennas with a gain of 20 dBi are used. The RF signal was later amplified with another LNA and HPA before downconversion using a broadband mixer. For demodulation of the QPSK signals, the RF signals were mixed with a copy of the 60 GHz local oscillator. An electrical phase shifter was used in the LO to tune the phase, and thus the I and Q baseband components were demodulated, one at a time. The eye diagrams of the demodulated I and Q data are shown in Fig. 13.

The baseband data were directly fed into a bit error rate tester (BERT) to measure the BER of the demodulated signals. BERs of \( 4 \times 10^{-8} \) and \( 8.7 \times 10^{-8} \) were measured for I and Q data, respectively. The BER shows a good quality of the 10 Gbits/s 4-QAM-modulated 60 GHz carriers. The quality can be further improved by increasing the optical power input to the photodetector, and by using high-gain antennas, which will also improve the achievable transmission distance.

4. 60 GHz RoF System for Indoor >1 Gbit/s Transmission

In this section, we report on the use of the mode-locked Fabry–Perot laser (ML-FPL) diode described in Section 2 to perform first the frequency upconversion of a high-speed UWB radio signal from a carrier frequency of 4.5 to 60 GHz and second the frequency downconversion from 60 to 4.5 GHz. The upconversion relies on directly modulating the ML-FPL with the intermediate frequency (IF) radio signal while the downconversion uses an external modulator. The distribution of the optical radio signal over 50 m of optical fiber is also demonstrated.

To realize a wireless network capable of delivering high-speed data (>1 Gbit/s) with housewide coverage, it is necessary to deploy several radio access points (RAPs)
around the home, linked together by a wired backbone network to convey the data between the different high-speed picocells. In such a scenario, the support of an optical backbone combined with radio-over-fiber techniques has been demonstrated to be very efficient and advantageous to distribute the radio signal to the different RAPs while centralizing the main RF and baseband functions at a single location [6]. In this architecture, three main functions are needed: frequency upconversion, frequency downconversion, and signal distribution over up to 100 m. In this section, we will at first describe the radio signal standard that we are using for our experiments. Then, we describe a system using advanced photonic components capable of realizing the three functions cited above.

4.A. IEEE802.15.3c Radio Signal
In the experiments below we use a radio signal taken from the IEEE 802.15.3c prestandard [23]. We chose the orthogonal frequency-division multiplexing (OFDM) variant among the different available modulation formats because it is the most susceptible to nonlinearity. The signal is generated with a sampling rate of 2.595 GHz and the 336 data subcarriers are QPSK modulated leading to a data rate of 3.03 Gbits/s. The 16 pilot subcarriers are used for signal equalization at the receive side. The criterion for the signal to be received successfully is to measure an error vector magnitude (EVM) [29] less than 23%. This value corresponds to an error rate lower than $10^{-6}$.

4.B. Frequency Upconversion and Distribution
The experimental setup is shown in Fig. 14. The radio signal under test is created on a PC using Matlab following the specification of the IEEE 802.15.3c group [23]. The signal is generated by a 10 GS/s dual-output arbitrary waveform generator (AWG), and both outputs (representing both $I$ and $Q$ components) are sent to a RF mixer to generate the radio signal on a 4.5 GHz carrier. At this point, the spectrum of the signal extends from 3.5 to 5.4 GHz and the available RF power is $-15$ dBm. In Figs. 14(b_TX) and 14(b_RX), this signal is subsequently amplified to approximately +15 dBm and is used to modulate the bias current of the ML-FPL (average bias current set to 260 mA). The optical output power out of the ML-FPL is +6 dBm. The laser pulses with a repetition rate of 54.8 GHz. Its modulation produces a mixing between the pulsating frequency and the IF carrier, leading to an optical frequency upconversion of the original signal to 59.8 GHz. To simulate the distribution of the radio signal within the home, 50 m of standard single-mode fiber (SMF) is used to link the laser to...
a commercial 70 GHz photodetector that is followed by a low-noise amplifier (LNA $G = 18$ dB from 55 to 65 GHz), a bandpass filter (58.5 to 64 GHz) and a high-power amplifier (HPA $G = 31$ dB from 59 to 63.5 GHz). The available RF power at this point is +4 dBm. To take a reference measurement, an all-electronic upconverter is used for comparison. The signal out of Fig. 14(a) is amplified to approximately 0 dBm and sent into a commercial mixer fed with a +10 dBm, 54.5 GHz local oscillator. The output RF signal is filtered, and a power of −13 dBm is obtained. In Fig. 14(d), to measure the quality of the received 60 GHz radio signal out of Figs. 14(b) or 14(c), it is first attenuated to the optimal power level (around −22 dBm); then it is downconverted using a conventional electrical mixer fed with a 54.5 GHz LO, and finally, it is captured using a 40 GS/s real-time scope. OFDM demodulation and EVM evaluation are performed offline using Matlab. Each capture records a total of 44 OFDM symbols over 10 $\mu$s, representing 296,000 bits of data.

Results are presented in Fig. 15. The spectrum of the received OFDM signal and the associated constellation diagram obtained after demodulation are shown. The mean EVM is 10.5% for a signal-to-noise ratio (SNR) of 23 dB. For reference, the results using an all-electronic upconversion (as depicted in Fig. 15, right) yield an EVM of 9% with a SNR of 25.2 dB. The results are marginally better, but it has to be underlined that the photonic upconversion provides as well the ability to transport and distribute the 60 GHz radio signal over several tens of meters. These results validate the use of the ML-FPL for radio signal upconversion and transport.

4.C. Frequency Downconversion and Distribution

The experimental setup is depicted in Fig. 16. The OFDM signal under test is created on a PC using Matlab and generated by a 10 GS/s AWG with its bandwidth centered at 1.6 GHz. It is then upconverted using a RF mixer in the IF band 4.8–7.0 GHz [Fig. 16(a)]. The IF signal is electrically upconverted to 60 GHz [Fig. 16(a$_{up}$)] then sent through the photonic downconverter [Figs. 16(b$_{TX}$) and 16(b$_{RX}$)] before analysis [Fig. 16(c)]. The analysis of Fig. 16(c) uses a 50 GS/s real-time scope to capture the output IF signal. OFDM demodulation and EVM evaluation are then performed offline using Matlab. The operating principle of the photonic downconverter is the same as in the upconversion scheme. The incoming mm-wave OFDM signal modulates

![Photonic upconversion](image1)

![Electrical upconversion](image2)

![Power dBm vs Frequency](image3)

![Power dBm vs Frequency](image4)

Fig. 15. Spectra (down) and constellations (up)—data and pilots—obtained after photonic upconversion (left) or electrical upconversion (right).
the MLL output through a 60 GHz Mach–Zehnder modulator (MZM, RF power of +7 dBm). The MZM is connected to a 10 GHz PD with SMF. The original 60 GHz OFDM signal is thus downconverted to approximately 5 GHz (the radio carrier frequency minus the MLL pulse frequency). The RF power at PD output is typically as low as −50 dBm.

Spectra of the received OFDM signal and associated constellation diagram obtained after demodulation are shown in Fig. 17. The mean EVM is 15.2% for a SNR of 20.9 dB. The obtained experimental EVM validates the use of the ML-FPL for radio signal frequency downconversion and transport.

5. 60 GHz RoF System for Uncompressed HDTV Transmission
Another key application of the developed broadband RoF technology is seen in enabling the wireless transmission of uncompressed high-density video/audio (HD
V/A) signals. Transmitting uncompressed HD V/A signals using a 60 GHz wireless system would not only preserve the best video and audio quality but also avoid encoding latencies. Even more important would be the fact that such systems would offer reduced complexity and lower cost by utilizing the license-free 60 GHz band and neither a video encoder nor a decoder would be required. On top of this, a 60 GHz wireless HD V/A link would further be free from interference with other existing wireless standards at 2.4 GHz, 5 GHz, or UWB. These advantages clearly justify the development of a 60 GHz RoF wireless link technology for HD V/A transmission.

For the wireless delivery of a high-quality uncompressed 1080p HD V/A signal, a maximum data rate of approximately 3 Gbits/s is required. Because this data rate is significantly lower than the maximum data rate of 12.5 Gbits/s offered by the 60 GHz RoF system described in Section 3, we have developed a more compact and significantly less costly 60 GHz RoF wireless link system that is especially suited for HD V/A wireless transmission over several meters.

Fig. 18. Setup of the constructed 60 GHz RoF wireless link for transmitting high-density video/audio signals. The optical mm-wave generation and modulation unit just consists of a 60 GHz band mode-locked laser diode. For simplicity and cost reasons, the constructed 60 GHz wireless receiver utilizes an envelope detection concept.

Fig. 19. Photo showing the developed units of the 60 GHz wireless HD V/A link. The optical mm-wave generation and modulation unit (top right-hand module) is put on top of the 60 GHz wireless RoF transmitter (bottom right-hand module). The 60 GHz wireless receiver can be seen on the left-hand side of the photo.
The system configuration of the 60 GHz RoF HD V/A wireless link system is shown in Fig. 18. As can be seen, the optical mm-wave generation unit of the system only consists of a single 60 GHz MLLD as described in Section 2, which can be either directly or externally modulated with the serialized HD V/A signal. This way, the necessity for the two MZMs required for the 12.5 Gbits/s system (see Fig. 5) was avoided for the sake of significantly reduced cost and complexity. It should be pointed out here that, of course, only the optical mode-locking frequency of the MLLD is in the mm-wave range; the laser itself only requires a low-cost fiber-optic package. In the wireless transmitter unit of the 60 GHz RoF HD V/A system, we employed the developed photodetector described in Section 2. Due to the relaxed system requirements as compared with the 12.5 Gbits/s system, the wireless receiver of the HD V/A system can accomplish a much higher noise figure, and thus we made use of a simpler envelope detection approach. This way, not only were costly phase-locked loops or self-heterodyning mixers avoided, but this receiver approach also allows the use of a MLLD with a mode-locking frequency slightly different from 60 GHz. This is possible because the 60 GHz band offers sufficient bandwidth (about 7 GHz), and thus the mode-locking frequency of the MLLD can vary slightly within a range of 1–2 GHz. Since the mode-locking frequency of the MLLD depends on the length of the laser chip (see Section 2), a less stringent requirement significantly increases yield and reduces the cost of the MLLD. The actual MLLD employed in the system has a mode-locking frequency of 58.8 GHz.

Figure 19 shows a photograph of the developed wireless system. On the right-hand side of the photo, the optical mm-wave generation and modulation unit that was placed on the 60 GHz wireless transmitter unit can be seen. Since optical fiber enables the low-loss transport of the 60 GHz signal over several kilometers, the optical unit can be placed far away from the transmitter, e.g., close to a recording HD camera. The size of the constructed optical generation/modulation unit is approximately $10 \times 20 \times 8$ cm$^3$. The wireless receiver can be seen on the left-hand side of the photo. It should be noted that the wireless path length between the transmitter and receiver was 10 m, but with respect to the results reported in Section 3, we expect a wireless path extension up to the kilometer range.

Using the developed 60 GHz RoF HD V/A wireless link system, the transmission of high-definition video/audio signals was successfully demonstrated. Figure 20 shows the developed compact wireless HD TV system displaying a 1080i HD V/A movie. This system was showcased at the ICT 2008 event.

6. Conclusions
Advanced photonic components and radio-over-fiber techniques for broadband wireless communications have been studied in this paper. Mode-locked FP lasers utilizing a quantum-dash active material and advanced broadband photodiodes were developed for 60 GHz signal generation. Utilizing those components and RoF techniques we developed a photonic wireless link and demonstrated wireless transmission at data
rates of 10.3125 Gbits/s over 40 m of air with the potential of wireless path extension into the kilometer range. Also, we reported on a photonic vector modulation approach for generating a 10 Gbits/s 4-QAM/QPSK-modulated 60 GHz carrier required for future spectrally efficient wireless systems. Furthermore, we developed a home-area wireless 60 GHz UWB system capable of carrying data up to 3 Gbits/s, and finally, we demonstrated a compact photonic wireless 60 GHz RoF link for transmitting uncompressed HD video/audio signals at speeds exceeding 3 Gbits/s.

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