Design and Investigation of Photonic Remote Antenna Units for Bidirectional Transmission in the Last Mile Wireless over Fiber System

Anna ŁYSIUK, Konrad GODZISZEWSKI, Yevhen YASHCHYSHYN, Józef MODELSKI

Institute of Radioelectronics, Warsaw University of Technology, Nowowiejska Street 15/19, 00-665 Warsaw, Poland

a.lysiuk@ire.pw.edu.pl, k.godziszewski@ire.pw.edu.pl, e.jaszczyszyn@ire.pw.edu.pl, j.modelski@ire.pw.edu.pl

Abstract. *In the article three different photonic Remote Antenna Units (RAU) in the last mile Wireless over Fiber links are presented. For construction of RAU commercially available optoelectronic devices were used. The solutions differ from each other by the method of ensuring isolation between transmitting and receiving modes of operation. All RAUs were designed, realized and measured in various scenarios. The results prove that all propositions can be successfully applied to uplink and downlink IEEE 802.11b/g wireless LAN systems, employing Wireless over Fiber technique.*

Keywords

Wireless over Fiber (WoF), photonic antenna, bidirectional transmission.

1. Introduction

Nowadays a continuous progress in new generation services offered to the users of communication systems led to the need for very rapid development of both backbone and access networks. The strongest growth is visible for wireless systems, which offer mobility, flexibility, ease of installation and modernization of the network. Modern wireless devices such as: mobile phones, laptops, tablets etc., stimulate the development of services that combine simultaneous transmission of voice, data and multimedia content, resulting in the need to ensure the requirements for the transmission parameters for each of them. These requirements include: high capacity, high data rate, the security of transmitted information, system reliability, scalability and flexibility.

As a response to the growing needs optical and microwave domains properties have been combined in Radio over Fiber (RoF) systems [1], [2]. Those systems, demonstrated e.g. in [3], [4], are capable of transmission of radio frequency carriers, carriers with digital modulation (16 QAM, 64 QAM, OFDM) or signals of particular standards (WLAN, UMTS, LTE) in lower (below 6 GHz) and upper (above 60 GHz) frequency bands [5], [6]. Depending on the assumed RoF link properties the electro-optic conversion can be based on simple direct modulation with the use of various kinds of lasers: DFB, FP, VCSEL [7] or external modulation scheme [3]. Also the possibility to use cheaper multi-mode [8] or plastic [9] optical fibers has been investigated in RoF systems, in the comparison to standard single-mode fibers.

To use the advantages of fiber-optic communication, while leaving the benefits of wireless transmission, such as flexibility and the ability to develop and modify the structure of the network, an idea of Wireless over Fiber (WoF) systems has been introduced [7], [10]. The WoF technique involves the transmission of radio frequency signals between one Central Station (CS), and a number of Remote Antenna Units (RAU) by means of optical fibers, while the communication between RAU and subscriber terminal is carried out in the wireless domain. The use of WoF technique is a promising way to distribute wireless signals inside buildings, e.g. to provide Internet access in public places such as railway stations, subway tunnels, airports, universities, shopping centers and sports facilities. Wide bandwidth and low loss of optical fibers allow the gradual introduction of new transmission standards, which can assume other broadcast frequencies and higher data rates. The specific architecture of the system will allow making these changes without interfering with the already created infrastructure.

One of the most important elements of WoF system is RAU station, which is the last element of transmission path between operator infrastructure and subscriber terminal. Those stations can be placed densely inside a building. Therefore, desired properties of RAUs are: compact structure, simple construction and low cost. This may be achieved by using the photonic antenna, whose concept is based on direct integration of high-speed optoelectronic components with microwave radiators [7], [11], [12]. The photonic antennas should effectively convert signal from optical domain to wireless microwave domain and vice versa. Such devices should also be characterized by wide frequency band covering frequencies which are used in wireless system for which the photonic antenna will be used. The wide frequency range depends on performance of both optoelectronic and microwave devices.

2. Bidirectional Transmission in WoF System

In WoF systems, dedicated for transmission of WLAN or LTE signals, the connection between CS and user terminal has to be bidirectional (downlink and uplink). The solutions for wired part of the system, between CS and RAU, are widely described in the literature [13], [14]. The bidirectional transmission can be achieved with the use of e.g. two separate fibers, optical circulators or WDM (*Wavelength Division Multiplexing*) couplers.

In the bidirectional RAU transmitting and receiving photonic antennas have to be used. Therefore, there is a need of isolation between signals transmitting in opposite directions. This is an important issue in designing radio electronic devices. The strong transmitting signal cannot be led to the sensitive receiver, which is dedicated to work rather with signals of relatively low levels. Furthermore, the transmitting signal can interfere with the received signal and reduce SINR (*Signal to Interference plus Noise Ratio*) of the whole link. Therefore there is a need of suitable isolation between transmitting and receiving paths or disconnection of the receiver during transmission. The lack of sufficient isolation could also result in saturation of the laser diode caused by high level of the microwave signal from the photodiode. The consequence of this effect would be problems with the direct modulation of the laser current by the signal received by the radiator.

In the article three different constructions of RAU for achieving bidirectional transmission in WoF systems are presented. In the implementation of RAUs an emphasis has been placed on obtaining as high as possible isolation between transmitting and receiving modes. The first solution is based on the use of two separated radiators, one for each mode. In the second RAU opposing directions of transmission are separated with the use of microwave circulator. The third solution employs an idea of using orthogonal polarizations, horizontal and vertical.

Parameter	Value	Parameter	Value
laser type	DFB	photodiode type	PIN
peak wavelength	1310 nm/1550 nm	wavelength range	1100 nm÷1650 nm
RF bandwidth	3 GHz	RF bandwidth	3 GHz
RIN noise	-154 dBc	optical Return Loss	-45 dB
optical connector	FC/APC	optical connector	FC/APC
slope efficiency	0,14 W/A	responsivity	0,85 A/W (@ 1310 nm) 0.95 A/W (@ 1550 nm)
output optical power (max)	4 mW	input power saturation	10 mW
output isolation	30 dB	capacitance	0.6 pF

Tab. 1. Selected parameters of optoelectronic components used in designed antenna stations.

In all realizations of RAU only commercially available optoelectronic components were used. Due to small size, easy polarization and low cost the laser diode and photodiode in coaxial pigtailed packages were chosen. The selected parameters of FOL13F1MWI-R4-F7/FOL15F5MWI-R4-F7 laser diode from Furukawa Electric and PPDA-F photodiode from AgxTechnologies are summarized in Tab. 1.

2.1 RAU with Separated Photonic Antennas

The solution is based on using two separate radiators for uplink and downlink directions in WoF system. Each radiator is an "E-shape" patch designed on Rogers RO4003C dielectric substrate with permittivity $\varepsilon_r = 3.55$. In order to extend the frequency range of operation the substrate, on which the radiator is placed, and a ground layer are spaced apart at a distance of $h = 5.5$ mm. The microwave antenna operates in the rage of 2.34 GHz ÷ 2.92 GHz, in which the reflection coefficient is below -10 dB (Fig. 1). Such frequency range covers the 2.4 GHz ISM band, where IEEE 802.11b/g standards work and the selected bands of LTE system. In the band the antenna reaches a gain value of 10 dBi. High gain allows to compensate electro-optic and opto-electronic conversion losses.

The laser diode is integrated with one radiator (port 1) which operates in receiving mode. The photodiode is connected to the second radiator (port 2) which works as transmitting antenna. In the experiment two "E-shape" radiators were used, both placed on the same dielectric substrate and distant from each other of $d = 50$ mm (Fig. 2). Such placement allows to achieve isolation between antenna ports around 25 dB in the frequency range of 2.3 ÷ 2.7 GHz.

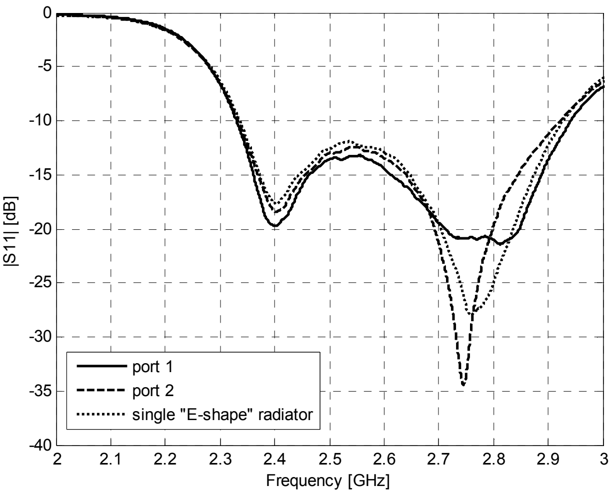


Fig. 1. Reflection coefficients of microwave "E-shape" antenna with separate radiators and single "E-shape" radiator.

In designing RAU the ground layer of the antenna is also the ground layer of the bias circuit board. The circuit was designed on a cheap FR4 laminate with thickness of $h = 1$ mm. This circuit contains a DC power connector, 5 V fixed voltage regulator (*IC*1) with blocking capacitors (*C*1, *C*2 = 1 μF), inductances (*L*1, *L*2 = 33 nH) separating the power supply from the microwave part of the board and $R1 = 100\ \Omega$ resistor, which sets the operation point of the laser diode to the value of 40 mA.

In Fig. 2 front, side and back view of the RAU with separated photonic antennas are shown.

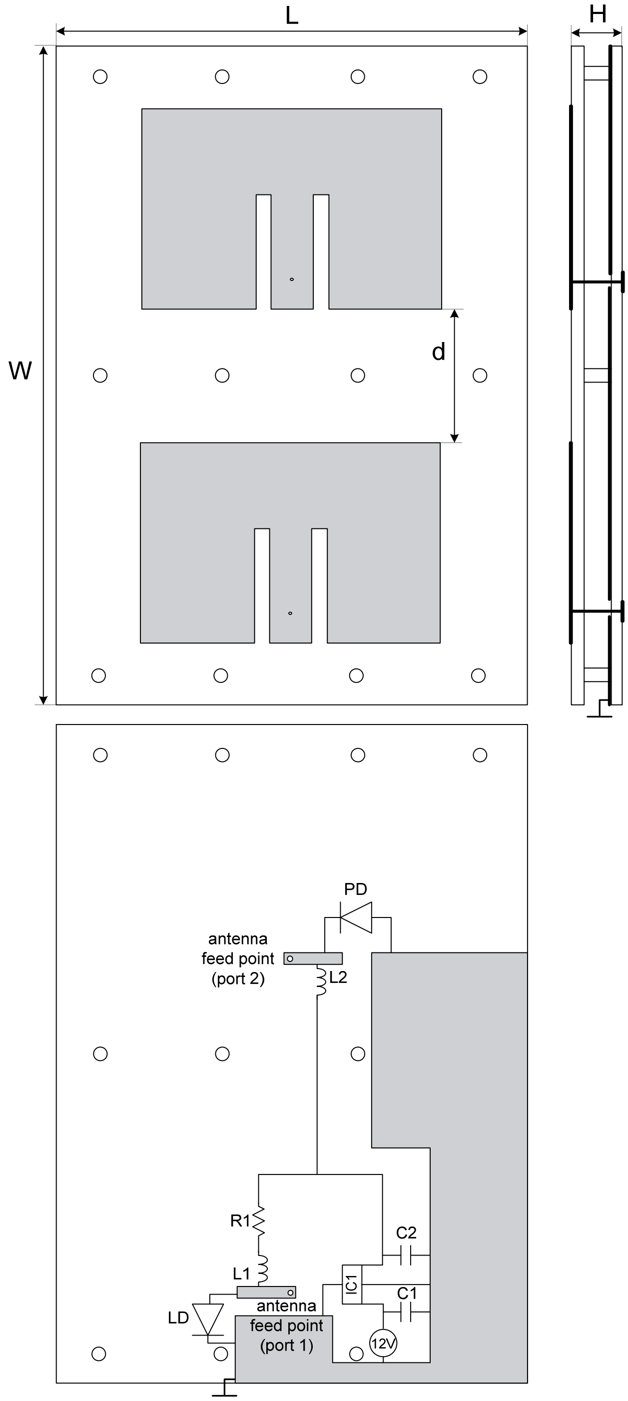


Fig. 2. Front, side and back view of the RAU with separated photonic antenna.

Radiators and appropriate microstrip lines leading microwave signal from the photodiode or to the laser diode are connected to each other by unshielded wire separated from the ground. The overall dimension of the RAU does not exceed the value of $W = 170$ mm, $L = 110$ mm, $H = 8.5$ mm. The upper radiator is connected to the photodiode and used in transmitting mode. The lower radiator with the laser diode operates in receiving mode. Antenna and the bias board are placed in a plastic housing. Power connector and optical connectors are placed outside the enclosure. The total size of the RAU is 190 mm × 150 mm × 50 mm.

The maximum gains of the RAU in frequency range were measured for both transmission modes and are plotted in Fig. 3. In case of photonic RAU the gain takes into account the following factors: 1) directivity of radiator, 2) antenna radiation efficiency, 3) mismatch efficiency between radiator and O/E and E/O devices, 4) conversion efficiency of photodiode (responsivity) or laser (slope efficiency), 5) influence of the dc bias circuit and ungrounded laser packaging.

In transmitting mode the gain of the RAU is mainly related to the responsivity of the photodiode and in receiving mode to the slope efficiency of the laser diode. Therefore the result for receiving mode is much lower than in transmitting mode. It should be emphasized that in RAU no additional microwave or optical amplifier was used. The use of amplifier could be discussed for receiving mode in the content of increasing the link gain. The studies of this research were conducted and described in [16]. In Fig. 3 the gain for receiving mode with microwave amplifier placed before laser diode is also plotted.

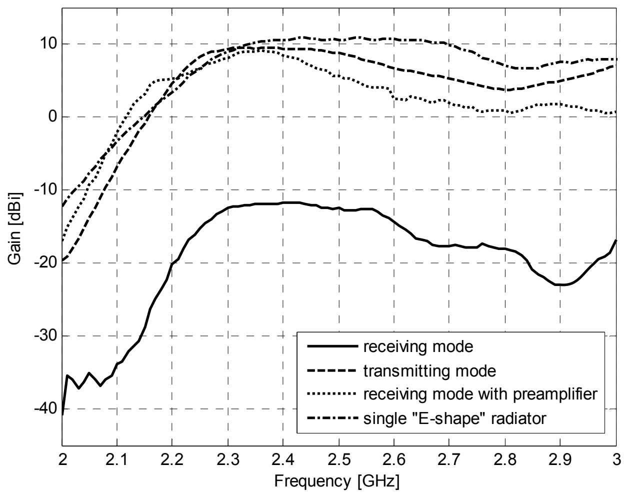


Fig. 3. Maximum gains vs. frequency measured for transmitting and receiving modes for the RAU with separated photonic antenna.

The partial gains in H-plane and E-plane for microwave "E-shape" antenna and RAU with separated radiators are plotted in Fig. 4. The measurements were performed for 2.45 GHz. Beside the gain level, as it has been shown in Fig. 3, the main differences in space distribution of the gains for photonic RAUs are connected with factor 5, mentioned before. It can be seen that these differences are well recognized in backward direction where levels of interacted fields are comparable.

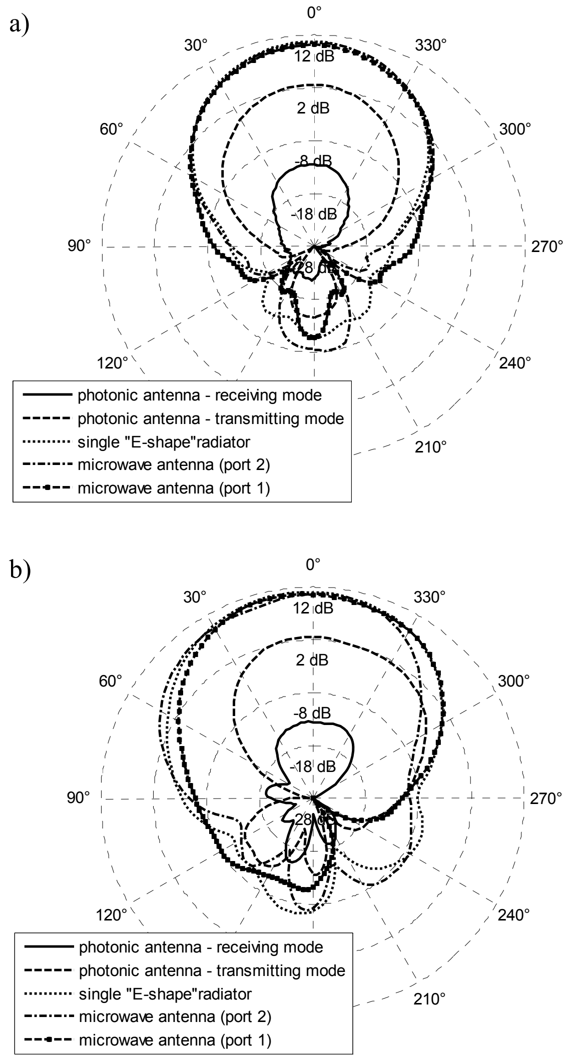


Fig. 4. Gains in H-plane (a) and E-plane (b) measured for microwave "E-shape" antenna and the RAU with separated photonic antenna.

2.2 RAU Based on Photonic Antenna with Microwave Circulator

The second construction of RAU consists of the photonic antenna and microwave circulator. The radiator is „E-shape" radiator as in paragraph 2.1. On the back side of the photonic antenna a microwave circulator is placed (RADITEK RADC-2.3-2.7-MSS-0.2WR-M). To the first port of the circulator a photodiode is connected. Therefore the optical signal in transmitting mode is converted to electrical domain by the photodiode and led to the second port of the circulator which is connected to the antenna feed point. In the receiving mode the signal detected by the antenna is directed to the third port of circulator and modulates optical carrier of the laser diode connected to this port. The front, side and back view of the antenna are shown in Fig. 5 ($W = 80$ mm, $L = 110$ mm, $H = 8.5$ mm).

This circuit on the back side of the RAU contains a DC power connector, 5 V fixed voltage regulator (*IC*1) with blocking capacitors ($C1$, $C2 = 1$ μF), inductances and capacitors ($L1$, $L2 = 33$ nH, $C3$, $C4 = 1$ μF) separating the power supply from the microwave part of the board and $R1 = 100\ \Omega$ resistor, which sets the operation point of the laser diode to the value of 40 mA. Antenna and the power supply board are placed in a plastic housing. Power socket and optical socket are placed outside the enclosure. The total size of the RAU is 140 mm × 100 mm × 40 mm.

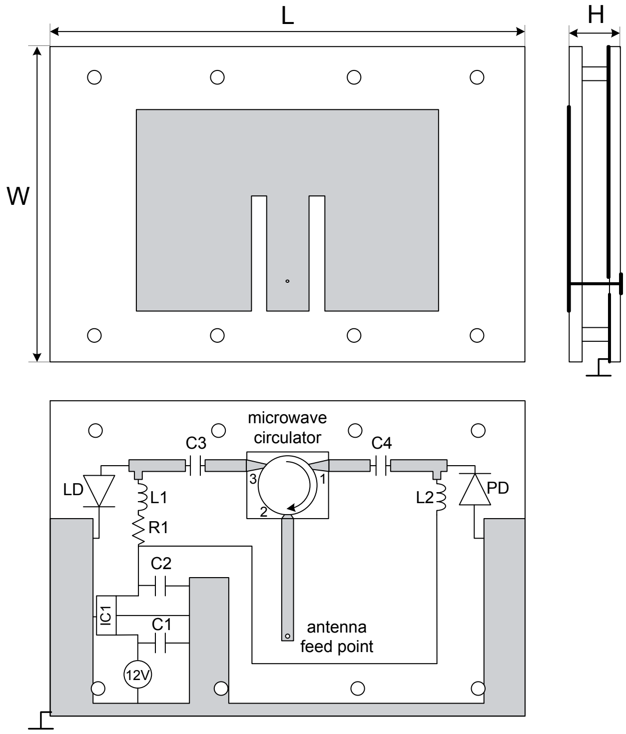


Fig. 5. Front, side and back view of the RAU based on photonic antenna with microwave circulator.

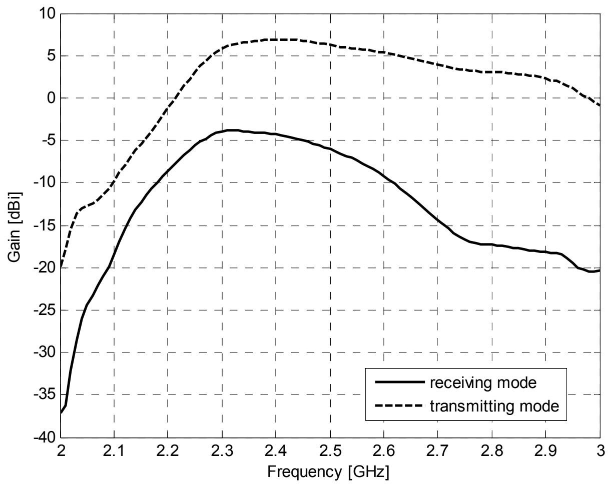


Fig. 6. Maximum gains vs. frequency measured for transmitting and receiving modes for the RAU based on photonic antenna with microwave circulator.

The maximum gains vs. frequency of the RAU based on photonic antenna with microwave circulator were measured for both modes and are plotted in Fig. 6. The gains of the RAU in H-plane and E-plane are plotted in Fig. 7. The measurements were performed for 2.45 GHz. The gain of photonic RAU based on photonic antenna with microwave circulator takes into account the same factors as in case of RAU1 beside factor 3, which is mismatch efficiency between circulator and O/E and E/O devices.

As for the first RAU the gain for receiving mode is lower than for transmitting mode. The parameters of the circulator also influence on the properties of the RAU2. The main differences in space distribution of the gains are in backward direction and they are connected with influencing of the dc bias circuit and ungrounded laser packaging (see factor 5).

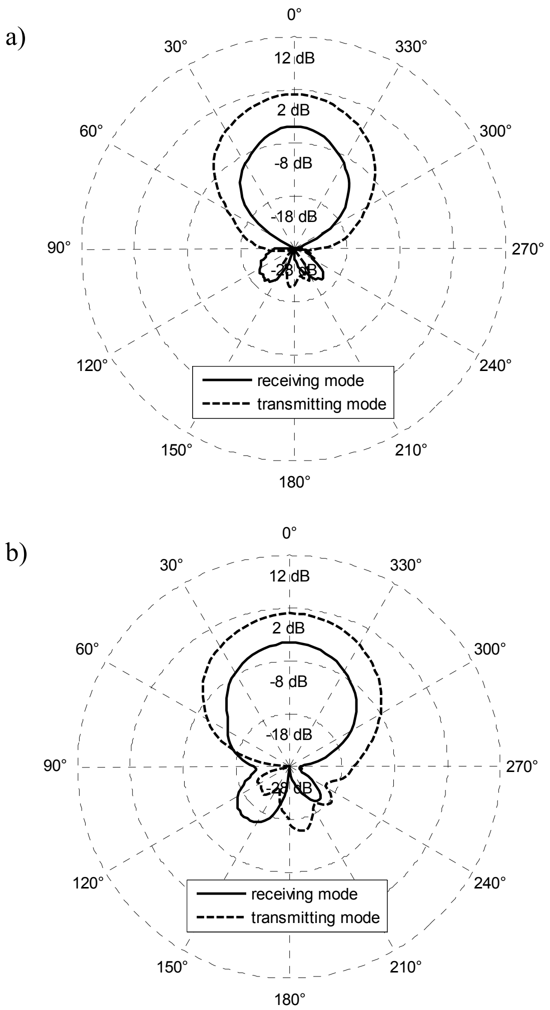


Fig. 7. Gains in H-plane (a) and E-plane (b) measured for transmitting and receiving modes for the RAU based on photonic antenna with microwave circulator.

2.3 RAU Based on Photonic Antenna with Orthogonal Polarizations

For realization of the third RAU a dual polarized coplanar CPW-fed slot radiator was designed and fabricated [15]. Exciting even and odd modes of the CPW line enables to achieve antenna working with horizontal and vertical polarization, respectively. The radiator was designed on a cheap FR4 laminate and operates in the frequency range of 2.3÷2.7 GHz. The reflection coefficients of two ports are plotted in Fig. 8. The achieved isolation between antenna ports is not worse than 21 dB. The gain is between 2 and 5 dBi depending on the port.

The first port (port 1) of the antenna is connected to the laser diode and the second port (port 2) to the photodiode. The transmission in transmitting mode is based on horizontal polarization, while in receiving mode a vertical polarization is used. Both optoelectronic elements are supplied from a single voltage source, stabilized by 5 V fixed voltage regulator (*IC*1) with blocking capacitors (*C*1, *C*2 = 1 μF), inductance (*L*1 = 33 nH) separating the power supply from the microwave part of the board and *R*1 = = 100 Ω resistor, which sets the operation point of the laser diode to the value of 40 mA. Dual polarized photonic antenna (Fig. 9, *W* = 100 mm, *L* = 80 mm, *H* = 1.5 mm) is placed in a plastic housing. Power connector and optical connectors are placed outside the enclosure. The total size of the RAU is 80 mm × 160 mm × 30 mm.

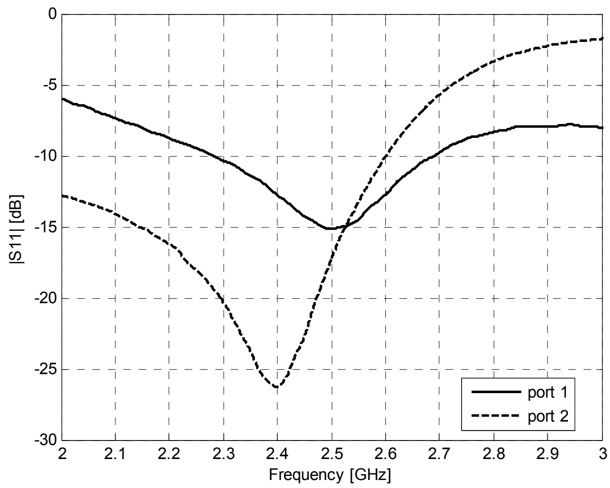


Fig. 8. Reflection coefficients of microwave dual polarized antenna.

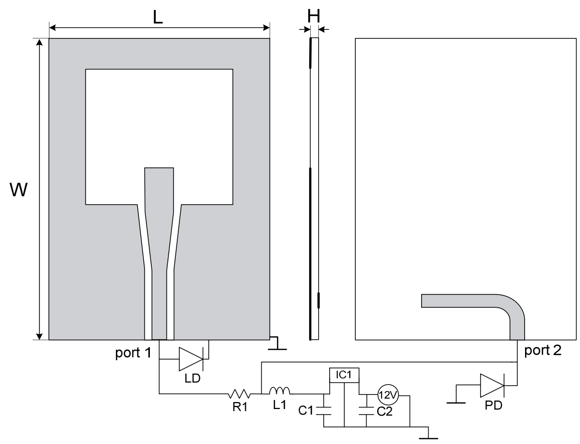


Fig. 9. Front, side and back view of the RAU based on dual polarized photonic antenna.

The use of different polarizations to transmit signals in different directions is justified in broadcasting systems inside buildings, where we deal with multipath propagation.

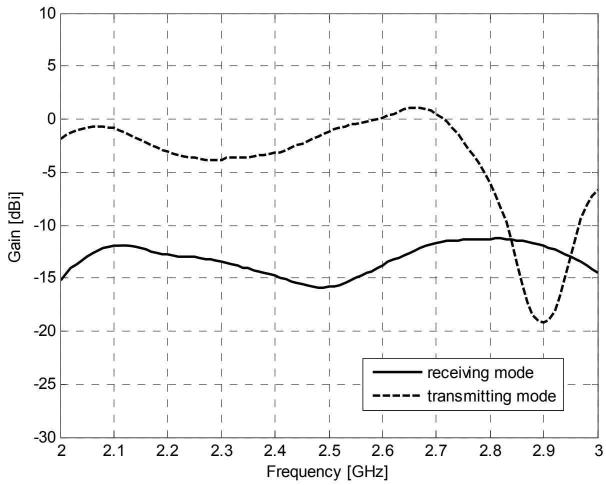
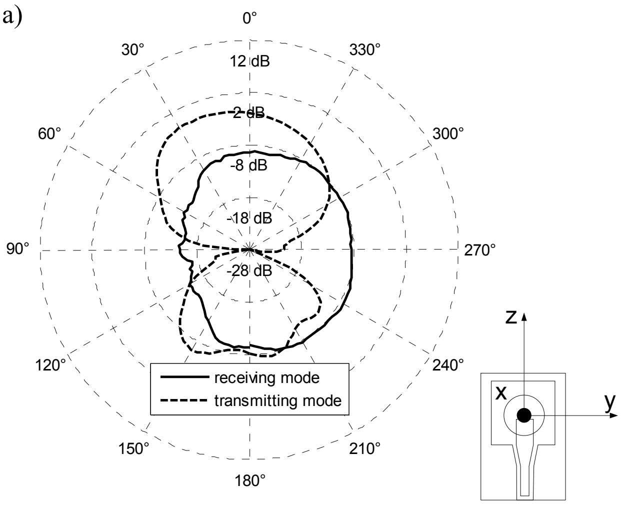


Fig. 10. Maximum gain vs. frequency measured for transmitting and receiving modes for the RAU based on dual polarized photonic antenna.

a)



b)

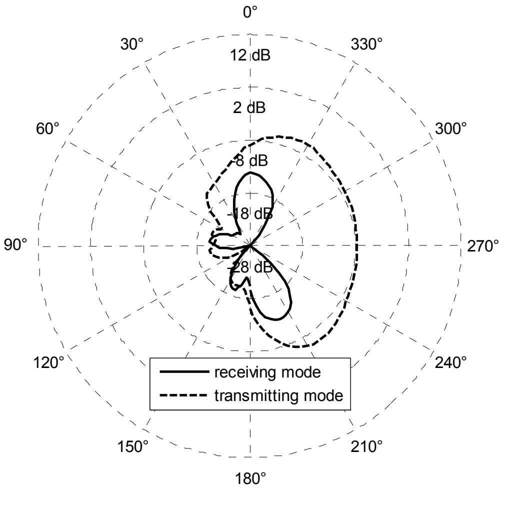


Fig. 11. Gains in xy plane (a) and xz plane (b) measured for transmitting and receiving modes for the RAU based on dual polarized photonic antenna.

The maximum gains vs. frequency in transmitting and receiving modes were measured and are presented in Fig. 10. The gain of photonic RAU based on dual polarized photonic antenna takes into account the following factors: 1) directivity of radiator in specified polarization, 2) antenna radiation efficiency in specified polarization, 3) mismatch efficiency between radiator and O/E and E/O devices, 4) conversion efficiency of photodiode (responsivity) or laser (slope efficiency), 5) influence of the dc bias circuit and ungrounded laser packaging.

As for previous RAU the gain for receiving mode is lower than for transmitting mode. The achievable gain is also lower than in case of RAUs described in paragraphs 2.1 and 2.2. It is a result of lower gain of dual polarized antenna than gain of "E-shape" antenna.

The gains for different polarizations for RAU based on dual polarized photonic antenna are plotted in Fig. 11. The measurements were performed for 2.45 GHz. During the measurements the polarizations of RAU and testing antenna were matched. For a given measurement plane the gains differ from each other because of different excitation type of each port. Additionally the gains are distorted by the influence of the laser packaging and connectors (see factor 5).

The gain characteristics presented in Fig. 11a correspond to typical RAU3 arrangement, which was used in all types of performed measurements.

2.4 Comparison of Designed RAUs

In paragraphs 2.1- 2.3 three different constructions of RAU for bidirectional transmission in WoF link were described. Presented transceiver antennas differ primarily in the type of radiator and methods of separation of transmit and receive signals. The parameters for each RAU are summarized in Tab. 2.

The use of separated radiators for transmitting and receiving modes is the easiest way to ensure isolation between the opposite transmission paths. This solution is characterized by high isolation (dependent on the distance between the radiators) in the order of 25 dB, but will double the overall size of the antenna, which may preclude its use in commercial systems.

	RAU1	**RAU2**	**RAU3**
radiator type	„E-shape”	„E-shape”	radiating slot
radiation pattern	directional	directional	non directional
min. isolation	25 dB	15 dB	21 dB
max. gain (trans. mode)	10,5 dBi	7 dBi	1 dBi
max. gain (rec. mode)	-12 dBi	-4 dBi	-12 dBi
dimensions	150 mm × 190 mm × 50 mm	140 mm × 100 mm × 40 mm	80 mm × 160 mm × 30 mm

Tab. 2. Comparison of the different solutions of RAUs.

The best results, in terms of transmission, are achieved in the link with RAU using microwave circulator. A weakness of this approach is limited isolation between transmission paths and the additional cost of the circulator (about $ 50 for assumed frequency range). The third proposal, which uses dual polarized antenna, is characterized by low values of the gains achieved in the transmitting and receiving modes, which is caused by the non directional operation. At the same time it provides a relatively high isolation between the orthogonal ports. Selection of the optimal solution is thus a compromise between different parameters of RAUs and it has to be made in the context of a particular application.

3. Quality of Signal and Throughput Measurements in WoF System

Developed WoF systems are dedicated for transmission of wireless standard signals such as IEEE 802.11 or LTE. According to the specifications of these standards signals are based on OFDM (*Orthogonal Frequency-Division Multiplexing*). OFDM is characterized by high spectral efficiency and is robust against intersymbol interference (ISI) and fading caused by multipath propagation. At the same time the main disadvantage of this kind of modulation is high peak to average power ratio (PAPR), what demands a linear transmitting and receiving paths. In order to determine how the E/O and O/E conversions influence on a quality of transmitted signal a comparison between traditional cable connection and WoF system is required. The level of distortion in the transmission path can be described with the use of two parameters: EVM (*Error Vector Magnitude*) and SNR (*Signal to Noise Ratio*). They represent the impact of nonlinear phenomena and introduced noise. Additionally, in transmission systems with high data rates, it is necessary to verify whether introducing of the RAU do not reduce the overall data rate offered to the users.

3.1 EVM Measurements

Described in paragraphs 2.1-2.3 RAUs were tested according to the scheme in Fig. 12. The Vector Signal Generator is a source of carrier modulated by simple QPSK, 16QAM, 64QAM signals and more complex IEEE 802.11 b/g standard signals.

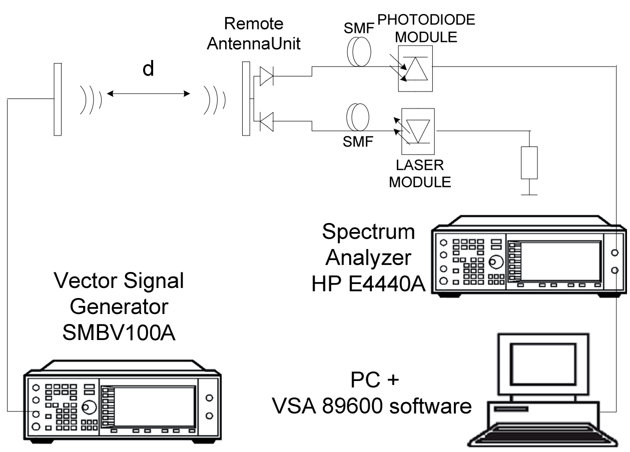


Fig. 12. Measurement setup for quality of signal measurements in uplink direction.

During measurements the signal transmitted in one direction is investigated, while the second path is loaded. In the uplink (Fig. 12) the signal from the generator is led to microwave antenna with known parameters, radiated and received by photonic antenna. The laser diode mounted on the antenna converts the electrical signal to the optical domain. The optical signal propagates across single mode fiber and is again converted into electrical domain in photodiode module. This signal is detected by Spectrum Analyzer connected to PC with VSA89600 software. The software enables to demodulate and analyze the received signal. At the output the EVM values are collected.

During the experiments WoF links with three RAUs were investigated in transmitting and receiving modes. Different kinds of signals were transmitted through the links and analyzed. In Fig. 13 the result of EVM error versus power detected by the analyzer in transmitting (a) and receiving (b) mode for IEEE 802.11g signal is presented.

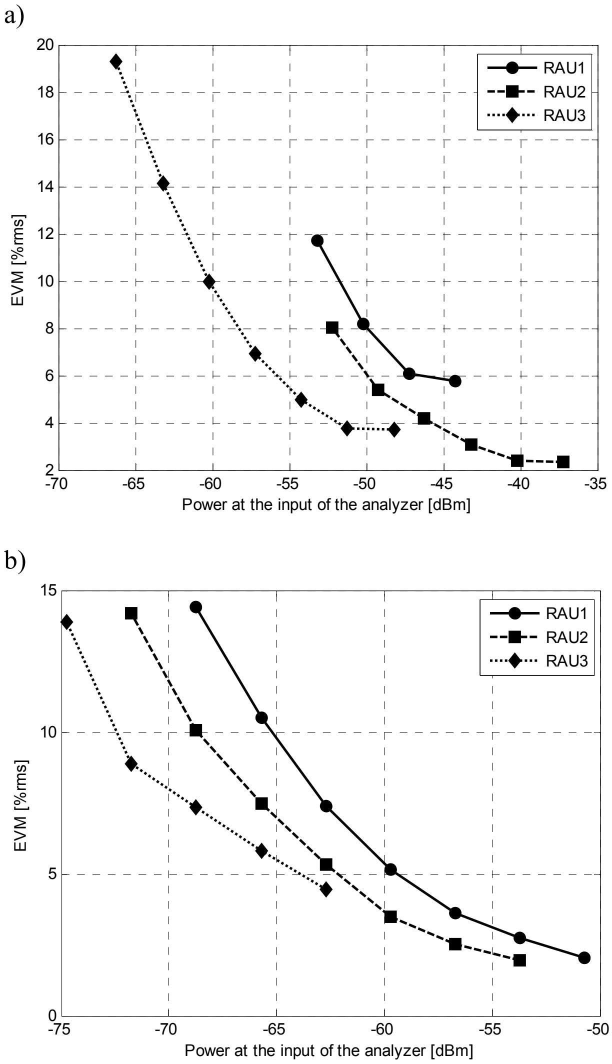


Fig. 13. EVM measurement results for all kinds of RAUs with the use of IEEE 802.11g signal in receiving (a) and transmitting (b) mode.

Measurements took place in a laboratory room in the presence of interfering signals coming from other WLAN and Bluetooth systems. Using all types of antennas and transmission for both modes it was possible to receive and demodulate signal even at low power levels at the input of the analyzer. In most cases, the best results are achieved for WoF link with the dual polarized antenna.

3.2 Throughput Measurements

From the users' point of view one of the most important parameters of the access network is achievable transmission rate, especially in the downlink direction. Therefore there is a need to verify whether the applying of WoF transmission will not influence the overall system performances under real working conditions. The WoF links with three kinds of RAUs were measured in the setup shown in Fig. 14.

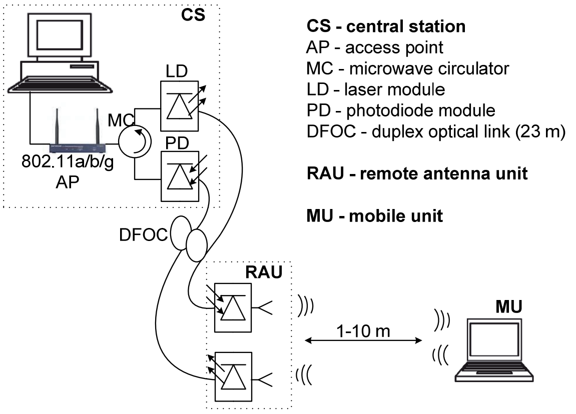


Fig. 14. Measurement setup for throughput measurements.

During measurements a PC connected to the access point *NETGEAR WAG102* via Ethernet cable was used as a central station. The access point (AP) was operating in infrastructure mode to allow connectivity to mobile users. AP antennas were removed and the uplink and downlink were separated from each other by means of microwave circulator (MC) *DITOM D3C2080*. The signal from the central station to the RAU and back was transmitted by single mode duplex optical link (23 m). RAUs consisted of investigated photonic antennas. Mobile user terminal was a laptop with integrated wireless card *Intel Centrino Wireless-N 1030*. The transmission can take place on a selected and fixed frequency channel. During the transmission distance between the RAU and mobile unit (MU) varied in the range of 1 to 10 m. Measurements took place in the real environment in the presence of active and passive interference signals. A transmission data rate at the TCP layer was examined. Measurements were conducted in uplink and downlink directions with a fixed data block length of 1460B. Network data rate was determined using the freeware program *Iperf*, installed on both computers in the central station and the user terminal. During the transmission access point parameters were set to the maximum possible data rate of physical layer. For IEEE 802.11b signal it is 11 Mbit/s and in the case of IEEE 802.11g signal 54 Mbit/s.

The first measurements were performed in a narrow corridor at the Institute of Radioelectronics, Warsaw University of Technology, Fig. 15. The height of a corridor is 2.6 m and the width is 2.7 m. The transmission performance of IEEE 802.11b/g signals were tested for all presented RAUs. The measurement results for 802.11g standard are shown in Fig. 16 in downlink (a) and uplink (b) directions.

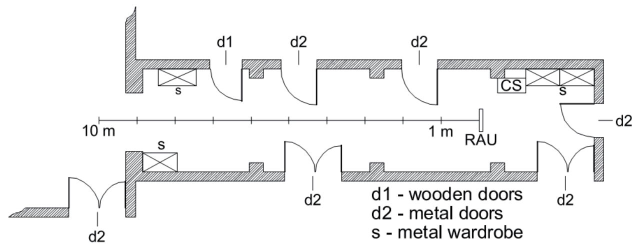


Fig. 15. The view of the first measurement scenario.

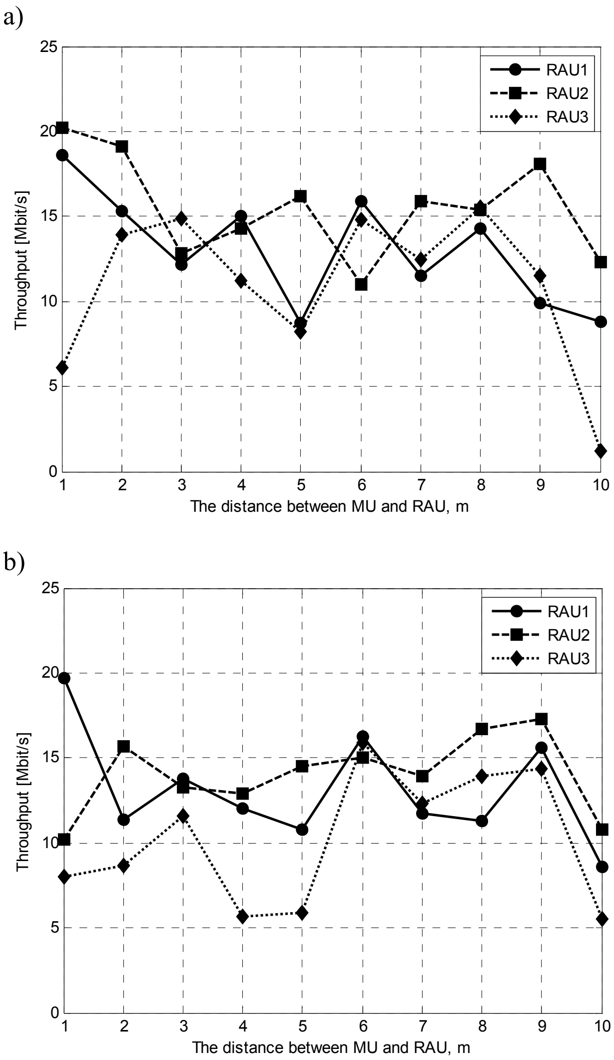


Fig. 16. Throughput measurement results in downlink (a) and uplink (b) direction.

The measurements took place in the real conditions, in the presence of passive and active interference signals. Excepting the network created for test, the MU terminal "saw" additional 5 WiFi networks working in the IEEE 802.11g standard. During the measurement operating channel was set to channel 9. This could cause decrease of data rate resulting from competition for access to the channel with a different WiFi networks. When analyzing the results a specific character of measurement setup need to be considered. Between CS and RAU a 23 meters long single-mode optical fiber was used, which delayed the signal.

In the case of IEEE 802.11b standard signals achieved transmission data rate for TCP layer were comparable with the corresponding theoretical value – 5.3 Mbit/s [17]. Slight worse results were achieved for WoF link with RAU3. It should be noted that in transmitting mode RAU3 was adapted for horizontal polarization, in comparison to the RAU1 and RAU2, which both operates in vertical polarization. Also the gain of RAU3 is lower than of RAU1 and RAU 2 in both modes. In the theory the throughput is dependent on a distance between RAU and MU. The higher throughput the lower sensitivity of the receiver what influence the value of achieved SINR. Results obtained in the transmission of IEEE 802.11g (Fig. 15) signals are much more variable as a function of distance from the RAU to MU. The reason for this situation may be the presence of other networks operating in this standard. In the case of RAU1 and RAU2 transmission data rates of 20 Mbit/s were achieved for a specific distance between MU and RAU. The maximum theoretical value for IEEE 802.11g standard is 24.7 Mbit/s [17]. In [18] similar results are shown. Beside measurements of throughput as a function of distance the dependence on the channel spacing between two networks operating in the same area was examined.

The second measurement scenario was prepared in a small lecture room with a height of 3.1 m (Fig. 17). During measurements 7 additional WiFi networks working in the IEEE 802.11g standard were available with high power levels. The operating channel had to be changed from 9 to 11 in the comparison to previous measurement due to high interference with other networks. The results for throughput measurement for IEEE 802.11 g signal in several measurement points are collected in Tab. 3.

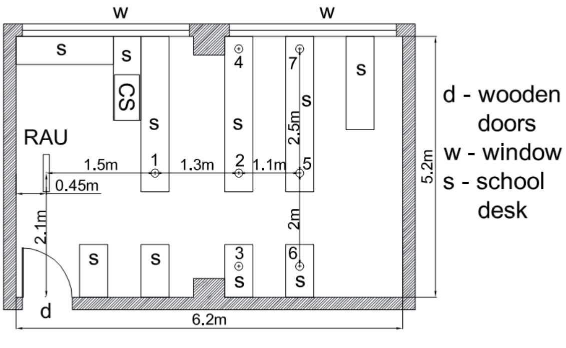


Fig. 17. The view of the second measurement scenario.

Presented results show that all RAUs behave similar to conventional WLAN networks. Irregularities which can be seen in throughput measurements are connected with multipath propagation inside the room and interferences from other networks. In places where interferences increase the throughput decreases. Considering all presented links and types of signals at any time, the communication between the subscriber terminal and the central station was maintained. This indicates that the WoF link can be successfully used in the WLAN networks.

meas. point	RAU1		RAU2		RAU3	
	rm	tm	rm	tm	rm	tm
1	14.8	6.5	14.9	19.7	16.3	6.8
2	17.5	18.6	17.2	15.3	18.5	12.8
3	16.9	4.5	4.5	3.8	4.8	0.7
4	17.1	6.0	10.8	5.3	11.2	3.7
5	13.8	5.2	12.6	4.3	11.0	3.9
6	12.4	7.0	7.8	1.1	9.8	3.5
7	8.3	1.9	9.9	5.9	12.2	1.3

Tab. 3. Throughput measurement results (Mbit/s), rm - receiving mode, tm - transmitting mode.

4. Conclusions

In the article three different constructions of bidirectional RAUs for WoF links were presented. The separation between transmitting and receiving modes of operation was realized only in microwave domain using two separated radiators, microwave circulator or orthogonal polarizations. The RAUs were compared in terms of electrical parameters and influence on quality of signal and throughput in WLAN network. Measurements results showed that the most critical link is from user's terminal to RAU. It is related to electro-optical conversion losses resulting from low slope efficiency value of the laser diode. The most important conclusion from the research is that in all three cases it was possible to maintain connection between MU and RAU and to achieve satisfying data rates and quality of signal values.

Acknowledgements

The article was supported by the Polish Ministry of Science and Higher Education, research project N N517 391038.

References

[1] IEZEKIEL, S. (red.) *Microwave Photonics*. John Wiley & Sons, 2009.

[2] GOMES, N. J., MONTEIRO, P. P., GAMEIRO, A. *Next Generation Wireless Communications Using Radio over Fiber*. John Wiley & Sons, 2012.

[3] MITCHELL, J. E. Performance of OFDM at 5.8 GHz using radio over fibre link. *Electronics Letters*, 2004, vol. 40, no. 21, p. 1353 - 1354.

[4] LIU, C. P, ISMAIL, T., SEEDS, A. J. Broadband access using wireless-over-fibre technologies. *BT Technology Journal*, 2006, vol. 24, no. 3, p. 130 - 143.

[5] SITTAKUL, V., CRYAN, M. J. A fully bidirectional 2.4-GHz wireless-over-fiber system using photonic active integrated

antennas (PhAIAs). *Journal of Lightwave Technology*, 2007, vol. 25, no. 11, p. 3358 - 3365.

[6] NG'OMA, A. FORTUSINI, D., PAREKH, D., YANG, W., SAUER, M., BENJAMIN, S.; HOFMANN, W., AMANN, M. C., CHANG-HASNAIN, C. J. Performance of a multi-Gb/s 60 GHz radio over fiber system employing a directly modulated optically injection-locked VCSEL. *Journal of Lightwave Technology*, 2010, vol. 28, no. 16, p. 2436 - 2444.

[7] SITTAKUL, V., CRYAN, M. J. A modular wireless-over-fibre (WoF) system using photonic active integrated antennas (PhAIAs). *International Journal of Microwave and Optical Technology*, 2010, vol. 5, no. 2, p. 105 - 114.

[8] SAUER, M., KOBYAKOV, A., GEORGE, J. Radio over fiber for picocellular network architectures. *Journal of Lightwave Technology*, 2007, vol. 25, no. 11, p. 3301 - 3320.

[9] LE GUENNEC, Y., DUCHAMP, J., MAURY, G., SCHIMPF, A., DOBREMEZ, V., BIDAUX, L., CABON, B. Multistandard transmission over plastic optical fiber. *IEEE Transactions on Microwave Theory and Techniques*, 2010, vol. 58, no. 11, p. 3109 - 3116.

[10] ISMAIL, T., CHUANG, C. H., SEEDS, J. Wireless data transmission of IEEE802.11a signals over fibre using low cost uncooled directly modulated lasers. In *Proceedings of the Asia-Pacific Microwave Photonics Conference*. Gold Coast (Australia), 2008, p. 70 - 73.

[11] LI, K., IZUTSU, M. Photonic antenna for wireless communication systems. *IEEJ Transactions on Electronics, Information and Systems,* 2004, vol. 124, no.2, p. 250 - 256.

[12] CHIZH, A., YASHCHYSHYN, Y., URZEDOWSKA, A., MALYSHEV, S., MODELSKI, J. Transmitting and receiving photonic antenna for radio-over-fiber systems. In *Proceedings of the 40th European Microwave Conference*. Paris (France), 2010, p. 129 - 132.

[13] DELAVAUX, J. M. P., GILES, C. R., GRANLUND, S. W., CHEN, C. D. Repeatered bi-directional 10-Gbit/s 240-km fiber transmission experiment. In *Proceedings of the Optical Fiber Communication conference.* San Jose (USA), 1996, p. 18-19.

[14] McDONNA, A. P., McCARTNEY, D. J., MORTIMORE, D. B. 1.3 µm bidirectional optical transmission over 31 km of installed single-mode fibre using optical couplers. *Electronic Letters*, 1984, vol. 20, no. 8, p. 722-723.

[15] LI, Y., ZHANG, Z., CHEN, W., FENG, Z., ISKANDER, M. F. A dual-polarization slot antenna using a compact CPW feeding structure. *IEEE Antennas and Wireless Propagation Letters*, 2010, vol. 9, p. 191-194.

[16] URZEDOWSKA, A., GODZISZEWSKI, K., YASHCHYSHYN, Y. Radio-over-fiber link for WLAN and LTE systems. In *Proceedings of the 19th International Conference on Microwaves, Radar and Wireless Communications*. Warsaw (Poland), 2012, p. 674 - 677.

[17] XIAO, Y., ROSDAHL, J. Throughput and delay limits of IEEE 802.11. *IEEE Communications Letters*, 2002, vol. 6, no. 8, p. 355 - 357.

[18] DOERING, M., BUDZISZ, Ł., WILLKOMM, D., WOLISZ, A. About the practicality of using partially overlapping channels in IEEE 802.11 b/g networks. In *Proceedings of the IEEE International Conference on Communications*. Budapest (Hungary), 2013, p. 3703 - 3707.

About Authors ...

Anna ŁYSIUK was born in Bialystok, Poland, in 1986. She received the M.Sc. degree in Telecommunication from the Warsaw University of Technology (WUT), Warsaw, Poland in 2010. She is currently working towards her Ph.D. degree in the Institute of Radioelectronics, Warsaw University of Technology. Her research interests include radio-over-fiber systems and antenna measurements.

Konrad GODZISZEWSKI was born in Warsaw, Poland, in 1986. He received the M.Sc. degree in Telecommunication from the Warsaw University of Technology (WUT), Warsaw, Poland in 2011. He is currently working towards his Ph.D. degree in the Institute of Radioelectronics, Warsaw University of Technology. His research interests include material characterization and antenna measurements.

Yevhen YASHCHYSHYN was born in Lviv, Ukraine, in 1957. He received the M.Sc. degree in Radioelectronics Engineering from the Lviv University of Technology (Ukraine) in 1979, the Ph.D. degree in Microwave Devices and Antennas from the Moscow Institute of the Electronic and Mathematics in 1986, and the D.Sc. degree (habilitation) degrees in Telecommunication from the Warsaw University of Technology in 2006. His research interests are: antenna theory and techniques, smart beamforming, reconfigurable antennas for communication and radar systems, and microwave photonics.

Jozef MODELSKI was born in Poland in 1949. He received his M.Sc., Ph.D. and D.Sc. (habilitation) degrees in Electronics from the Warsaw University of Technology in 1973, 1978 and 1987, respectively. In 1994 he obtained the state title of Professor. Since 1973 he has been with the Institute of Radioelectronics, Warsaw University of Technology (WUT), holding all academic positions from teaching/research assistant to tenured professor (1991). His research interests include: microwave modulators and shifters, dielectric resonators, integrating waveguide technology, material properties measurements and recently ferroelectric and smart antennas for communication systems.