Technologies and Applications of Microwave Photonic Antennas

Y. Yashchyshyn[#], A. Chizh[*], S. Malyshev[*], J. Modelski[#]

Abstract - **This paper describes the development of microwave photonic antennas concepts and their applications. The experimental study of the transmitting and receiving photonic antenna are shown. The transmitting photonic antenna consists of photodiode integrated with microstrip E-shaped patch antenna, and receiving photonic antenna consists of laser diode integrated directly with the Vivaldi antenna.**

Keywords – **Microwave photonic, photonic antennas, antennas, photodiode, laser, optoelectronic devises.**

INTRODUCTION

Nowadays subscribers require mobile access to the network inside their homes and offices. Simultaneously broadband access is required. Therefore not only high speed photonic-based internet access networks are desired but also conversion that enable usage of mobile, wireless terminals. Mobility can be combined with high speed data rates if extremely broadband techniques are applied. The wireless systems can provide high bit rates at short distances. In such system optical transmission is highly suitable between access point and the Internet provider. Systems combining ultra-wideband wireless transmission with photonic based networks will be thereafter referred to as hybrid RF-photonic systems or radio-over- fiber systems [1]. However, in such system two conversions are required. One from the RF signal to optical waves and second, at the other side – from optical waves back into RF. For that purpose additional module are required in every access point and every antenna. Nevertheless development in the area of such techniques is highly preferred. An obvious direction is miniaturization and integration of the photonic-based modules with RF devices that leads to reduction of the infrastructure cost.

In base-station architecture the existing optical access network infrastructure can be successfully used to deliver microwave communication signals between Network Controller and the antenna points by means of radio-over-fiber techniques [2]-[7]. A common optical network infrastructure would be shared among the several operators to provide different services. In comparison to conventional distribution networks based on coax cable, optical fiber distribution networks offer wide bandwidth capability, high electrical isolation, very low crosstalk, low RF attenuation and dispersion, immunity to electromagnetic interference. To reduce the installation and maintenance costs of such systems, it is imperative to make the radio antenna units as simple as possible. This may be achieved by using photonic active integrated antennas. The use of photonic-based antenna feeds opens the possibility of unique, very high performance antenna systems [8]-[10].

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PHOTONIC ANTENNA CONCEPT

Conventional microwave antenna usually has a microstrip or coaxial feeding line finished by the microwave connector. The microwave power is transmitted to and from the antenna by means of RF cable. In the photonic antenna, the RF cable is replaced by optical fiber, therefore it is necessary to use optoelectronic components, such as lasers and photodiodes, for the conversion of microwave signal to the modulated optical signal and vice-versa. Photonic antenna can be hybrid or monolithic (Fig. 1).

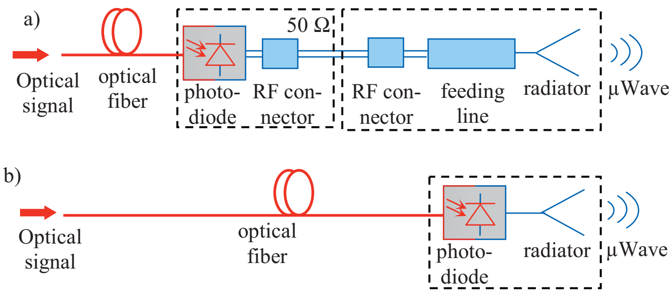

Fig. 1 Example of hybrid (a) and integrated (b) photonic antenna configurations

Hybrid photonic antenna consists of two independent parts: fiber-optic photodiode module and conventional microwave antenna, which are connected together by means of microwave connectors. In the monolithic photonic antenna, the photodiode is integrated with microwave antenna, and the photocurrent generated by photodiode directly excites the antenna. Photonic monolithic antennas have the following advantages:

- light weight and small size as photonic antenna does not require metal RF cables and connectors;
- the possibility of the remote antenna control due to low loss in optical fiber below 0.2 dB/km;
- wide bandwidth, which is limited only by the antenna itself;
- immunity to electromagnetic interference, which is important to the large antenna systems;
- the possibility to use optical signal processing and optical generation of microwaves in the antenna systems.

Let see the optoelectronic system. It consists of high-speed InGaAs/InP p-i-n photodiode module and high-speed laser diode module. Measurement signal can be led to or from the photonic antenna by means of fiber-optic cable.

The InGaAsP/InP p-i-n photodiode has front-illuminated p^+-region placed in a pigtailed fiber-optic module. To enhance the responsivity and to reduce the reflection from the fiber-air and air-chip interfaces, the special matching medium with refractive index close to that of quartz fiber has been placed between the chip and the fiber.

High-speed laser diode module represents the injection multiquantum-well strip InGaAsP/InP laser with Fabry-Perot resonator placed in pigtailed fiber-optic module. Fig. 2 shows the connection circuit of high-speed laser diode and photodiode modules, which consist of DC resistance *Rdc*, blocking capacitance *Cb* and inductance *Lb*, package capacitance *Cp* and inductance *Lp*, and coplanar transmission line with impedance $Z_L = 50\ \Omega$.

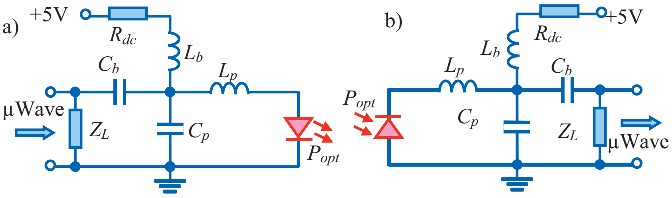

Fig. 2. Connection circuit of high-speed laser (a) and photodiode (b) modules.

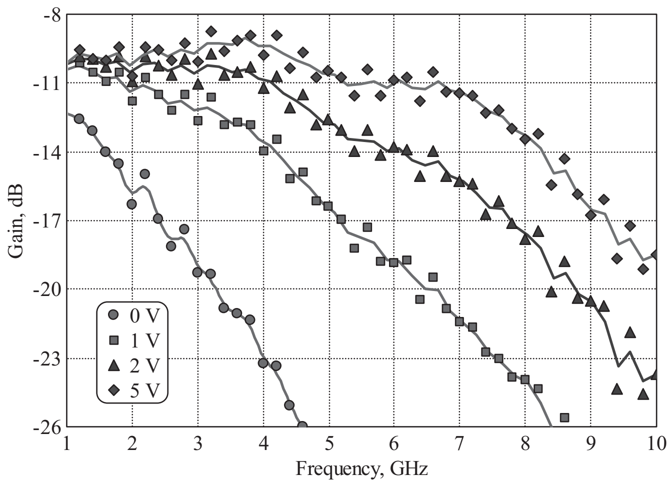

Fig. 3. Microwave gain of optoelectronic pair laser diode module – photodiode module versus frequency under different bias voltage of the photodiode.

Figure 3 shows the microwave gain of optoelectronic pair laser diode module – photodiode module versus frequency under different bias voltage of the photodiode. One can see that the bandwidth of optoelectronic pair at the level -3 dB is 8 GHz under bias voltage -5 V. It is worth noting that the photonic antenna can operate without bias voltage, although in this case, it is necessary to use photodiode with higher bandwidth.

TRANSMITTING PHOTONIC ANTENNA

It should be noted that only transmitting photonic antenna can be constructed basing on photodiode due to unilateral nature of the optoelectronic components. The main disadvantages of the transmitting photonic antenna are: relatively low output microwave power, limited by maximal photocurrent generated by the photodiode, which is usually not more than tens of milliamperes, and optoelectronic conversion loss, which can exceed 10 dB.

In case of the integrated photonic antenna, the photodiode is loaded directly with the input impedance of the microstrip patch radiator (Fig. 4).

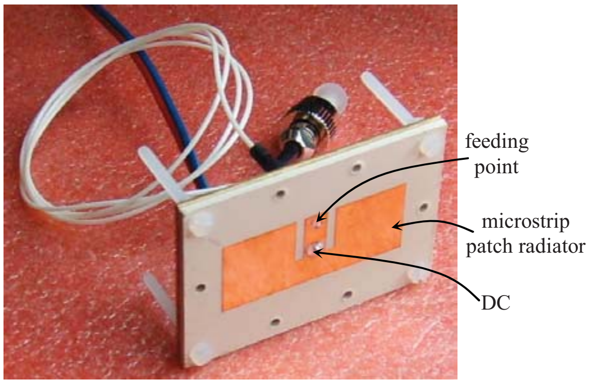

Fig. 4 Photo of the active integrated photonic antenna

The microwave signal is led to the photonic antenna by means of a single mode optical fiber as the amplitude modulated optical signal. The radiator is a rectangular E-shaped microstrip patch designed to operate at 5.8 GHz within 750 MHz frequency band. A microstrip substrate is used to mount the photodiode, which is soldered onto the backside of the antenna. The photodiode current can flow across the patch. The photodiode used in photonic antenna is the high-speed InGaAs/InP p-i-n photodiode with 8 GHz 3dB-bandwidth and 1.0 A/W sensitivity at the wavelength 1310 nm. The photodiode structure consists of 0.3 µm, $5{\cdot}10^{18}\,cm^{-3}$ p^+-InP top layer, 2.5 µm, $1{\cdot}10^{15}\,cm^{-3}$ n^0-$In_{0.53}Ga_{0.47}As$ absorption layer, 0.5 µm, $5{\cdot}10^{18}\,cm^{-3}$ n^+-InP contact layer, and n^+-InP substrate (Fig. 5). The diameter of photosensitive area is 40 µm.

Fig. 6 shows the equivalent electrical circuit of the investigated active integrated photonic antenna for high-frequencies. The microstrip patch is represented as complex impedance Z_i. The photodiode is represented by current source I_{ph}, p-n junction capacitance C_{pn} (0.07 pF) and resistance R_{pn}, as well as package capacitance C_p (0.5 pF) and inductance L_p (2 nH). From equivalent circuit one can see that the effective radiated power of the photonic antenna depends on the impedance matching between the photodiode and the microstrip patch. Since input impedance Z_i of the microstrip patch radiator depends on the feeding point position d_f there is optimal feeding point providing the highest antenna efficiency within the widest frequency band. In order to find optimal feeding point, a detailed knowledge of input impedance of both, the photodiode and the microstrip patch radiator at the desired frequency band is required.

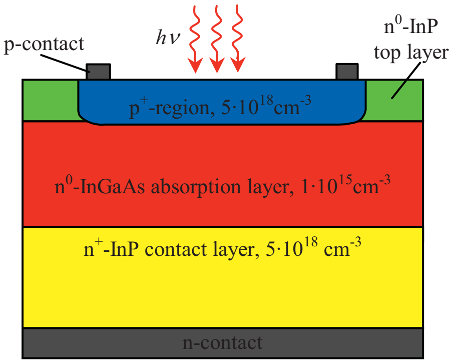

Fig. 5. Cross-section of the InGaAs/InP p-i-n photodiode

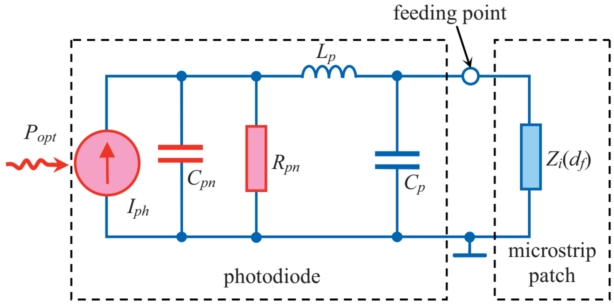

Fig. 6. Equivalent electrical circuit of the investigated active integrated photonic antenna for high frequencies

It shows that the input resistance of Z_i increases for higher frequency causing favourable conditions for matching photodiode. Nevertheless, the imaginary part, however, shows disadvantageous variation of the input impedance from the inductive to the capacitive behaviour. Both, the resistance and the reactance change with frequency, causing the antenna efficiency to be frequency dependent. The feed point position has been set to d_f = 2.3 mm. In this case, the resistance increases with frequency monotonically, while the reactance has a minimal variation.

The power supply point position has been set to d_{DC} = 7.1 mm, where active resistance equals to zero, and microwave signal is rejected.

Fig. 7 shows experimental setup for the measurement of the antenna gain. The measurement system consists of 2-D planar scanner and rotary table placed into the anechoic chamber and the block of measuring instruments from Agilent Technologies..

The whole system is managed by the computer. Source microwave signal is converted to intensity-modulated optical signal by means of high-speed laser diode module. Then, the optical signal is led to the photonic antenna by means of singlemode fiber-optic cable. Measurement microwave signal is led from antenna under test to the microwave receiver. So, in our experimental setup the photonic antenna (as a probe) is the radiating antenna, and the antenna under test is the receiving antenna.

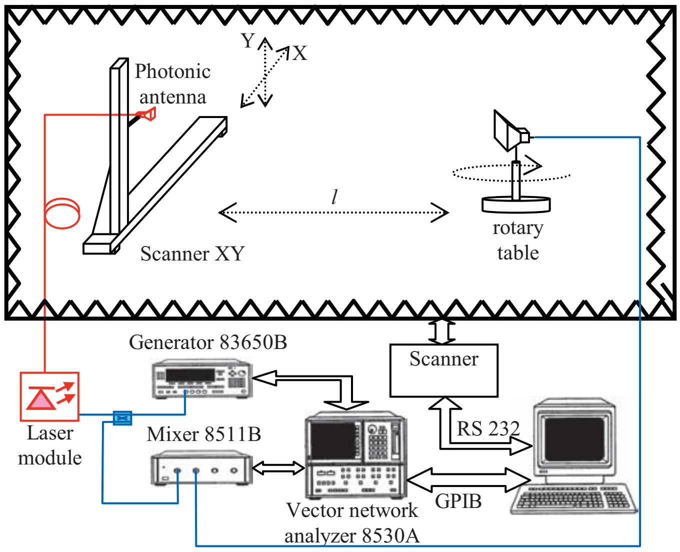

Fig. 7. Experimental set-up for the measurements of the photonic antenna gain

Fig. 8 shows the calibrated measured results for different measurement scenarios. The first one is the conventional scenario which means that the conventional antenna with SMA connector and cable feeder have been used. The second scenario means that the hybrid photonic antenna has been under investigation. In the hybrid photonic antenna, the antenna is connected with photodiode module through SMA connector. In the third scenario, the integrated antenna has been investigated. It is shown, as expected, that the gain of the integrated photonic antenna increases for higher frequency. The reason is the fact that for higher frequency, the input resistance of the patch antenna also increases and it, in turn, causes better matching of the photodiode with the radiator. In case of the both, hybrid and integrated photonic antenna, the same laser module has been used. During all measurement scenarios, the same RF power has been applied.

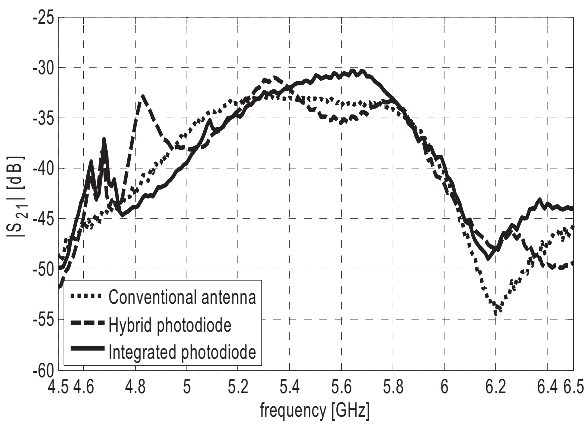

Fig. 8. S_{12} versus frequency for different measurement scenarios

Fig. 8 shows that the efficiency of the integrated photonic antenna can be increased by means of the optimal matching of the photodiode with the radiator.

RECEIVING PHOTONIC ANTENNA CONCEPT

In the receiving photonic antenna, the laser diode is integrated with microwave radiator, and the microwave current generated into the antenna modulates the output optical power of the laser. To achieve ultra wideband operation of the developed photonic antenna the Vivaldi radiator has been used. Antenna feed has been realized by means of microstrip line, which impedance changes from 50 to 120 Ω. Such feeding line has optimal matching with Vivaldi radiator and allows measuring antenna S-parameters using standard microwave equipment. To ensure travelling-wave mode in the microstrip feeding line the matching load of 50 Ω is placed at the one edge of the microstrip line and resistor of 120 Ω is soldered at the another edge of the line. The laser diode has been soldered at the edge of the microstrip feeding line in series to resistor of 120 Ω. The laser diode used in photonic antenna is the pigtailed InGaAsP/InP multi quantum-well distributed-feedback laser, which has emission wavelength 1311 nm and 20 mW output optical power in the fiber.

For study of photonic antenna characteristics the measurement system has been developed. Source microwave signal from generator Agilent 83650B is led to the measuring broadband TEM-horn antenna via 4 m-length coaxial cable. Measuring horn antenna irradiates microwave signal to the receiving photonic antenna. Intensity-modulated optical signal from receiving photonic antenna is led to the high-speed InGaAs/InP p-i-n photodiode module via single mode optical fiber. Photodiode module converts optical signal to microwave signal, which has been measured by vector network analyzer Agilent 8530A. The distance between the measuring horn antenna and receiving photonic antenna has been 3 m. The optoelectronic conversion losses have been in the range from 10 to 20 dB from 2.5 to 6 GHz and the ripples in the frequency response of the whole systems follows the ripples of the fiber-optic link. It means that these ripples are connected with frequency response of used fiber-optic photodiode module. Thus the developed receiving photonic antenna has flat frequency response in the studied frequency range. The preliminary investigation has shown that sensitivity of the receiving photonic antenna is around −75 dBm, which is limited by relative intensity noise of the laser diode.

The developed receiving photonic antenna is going to be investigated in the different UWB applications, e.g. in microwave imaging systems, UWB pulse location systems and WLAN communication systems.

CONCLUSION

The results of the investigations of the transmitting and receiving active integrated photonic antenna have been presented. The results of the comparison of the conventional fiber-optic link and the photonic antenna have been illustrated as well. It is shown that the efficiency of the receiving photonic antenna is depends on the relative intensity noise of the laser diode and that the efficiency of the transmitting photonic antenna can be increased by means of the optimal matching of the photodiode with the radiator, with no matching networks and no RF amplification The efficiency of the receiving photonic antenna can be additionally increased by means of the optimal matching of the laser diode with the radiator, with no RF amplification.

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