# Microwave Photonic Devices and Systems

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**Abstract -** In this paper, we review our recent work on novel high-speed photonic InP components and their application in millimeter-wave (mm-wave) fiber-wireless systems. In detail, the paper is concerned with ultra broadband travelling-wave photomixers and photodetectors, high-speed waveguide modulators, as well as novel electroabsorption transceiver elements. Besides the basic device concepts and properties, the employment of the high-speed photonic components in a mm-wave fiber-wireless network is experimentally demonstrated, showing for the first time, full-duplex broadband fiber optic transmission in a point-to-point link. Furthermore, point-to-multipoint fiber-ring networks will be discussed and in a first experiment full-duplex point-to-multipoint operation is experimentally demonstrated. Finally, an EMC optical microwave sensor is also described.

**Introduction** – Within the last decade, the field of microwave photonics [1,2] has attracted growing interest worldwide. Especially, the optical distribution of microwave and mm-wave signals in wireless applications such as fiber-wireless networks or antenna arrays is of great interest. Future wireless communication networks, for example, are expected to offer broadband multimedia services to a large number of subscribers. As a consequence, the radio frequency is expected to be within the mm-wave band, e.g. at 60GHz, where a sufficient bandwidth for the large number of broadband channels is available. Since the electrical transmission of the mm-wave radio signals over long distances is not feasible, fiber-wireless systems are considered to form the backbone of future broadband mm-wave wireless communication systems. Obviously, the successful implementation of mm-wave wireless communication networks in mass-market applications strongly depends on the costs of the infrastructure. In that respect, especially the cost of each single base station is a very critical factor. Consequently, it is of great interest to reduce the base station complexity and cost by using multifunctional and highly efficient mm-wave photonic devices.

In this paper, we present novel high-speed InP photonic components and discuss their application in mm-wave fiber-wireless systems. All components discussed in this paper are so called microwave-optical interaction devices using coplanar waveguides for the electrical signals and channel waveguides for the optical signal propagation at 1.55µm. In detail we present ultra broadband photomixers, travelling-wave (TW) photodetectors, high-speed electroabsorption modulators (EAM), and novel electroabsorption transceivers (EAT). Furthermore, we discuss the employment of these high-speed components in 60GHz millimeter-wave (mm-wave) fiber-wireless networks. Experimentally we demonstrate full-duplex broadband (156Mbit/s) fiber-optic transmission in the 60GHz band in a point-to-point as well as in a point-to-multi-point link, for the first time.

**Ultra broadband TW photomixer -** A schematic of the fiber-coupled travelling-wave (TW) photomixer [3] used in this work is shown in Fig. 1. The device consists of an optical channel waveguide and a hybrid microstrip/coplanar electrical transmission line. A tapered single mode fiber (SMF) with a transformation loss of 0.2dB is employed to efficiently couple light into the photomixer [4]. The core of the optical channel waveguide consists in this case of a multiple quantum well (MQW) section with a specified absorption coefficient @ 1.55µm wavelength. Thus 1.55µm light propagating along the optical waveguide is gradually absorbed, generating an electrical signal that travels along the electrical transmission line. Recently, such 1.55µm travelling-wave devices have been shown to overcome the RC limited frequency response, exhibiting superior high-frequency performances [5]. The photomixer presented here exhibits a DC responsivity of 0.43A/W @ 7V reverse bias and a maximum breakdown voltage in excess of 13V. The response up to 110GHz mm-wave frequency was measured employing an optical heterodyne set-up. The experimentally determined frequency response is almost flat up to 110GHz with a total signal roll-off from 26 to 110GHz of about 5dB, which is attributed to conductor losses. The maximum generated mm-wave output power at 110GHz was –21.5dBm. As expected, the generated mm-wave power shows a quadratic dependence on the optical input power. Furthermore, no saturation is observed up to an optical input power of +17dBm thus even larger output power levels can be expected. To our knowledge, this is the first experimental demonstration of an ultra broadband 1.55µm photomixer operating at least up to 110GHz with a record generated mm-wave power of –21.5dBm at 110GHz.

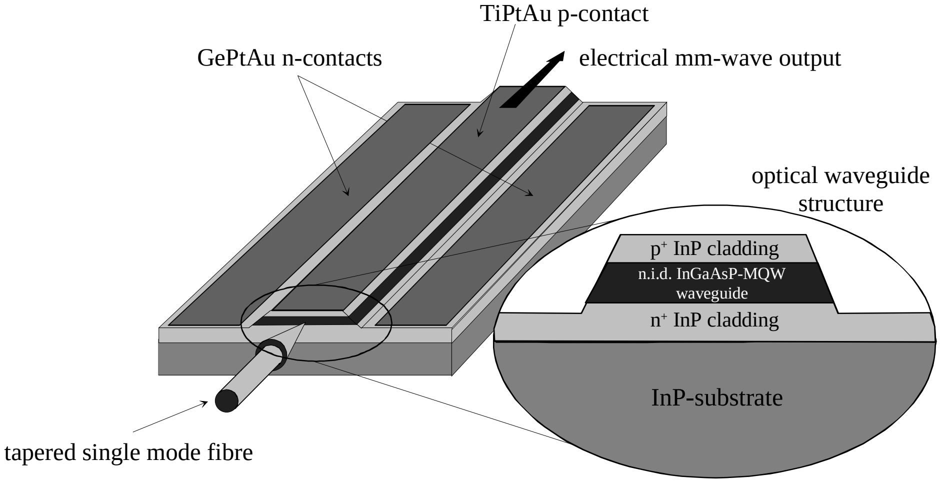

**Figure 1**: *Schematic of the fabricated TW photomixer.*

**TW photodetectors** – In another approach TW photodetectors (TW-PD) have been designed for the generation of 60GHz millimeter wave frequency signals in radio-over-fiber applications employing a heterodyne approach with two 1.55µm erbium-doped fiber-ring lasers. The basic concept of this TW-PD is that of Fig. 1 where the MQW waveguide has been replaced by a transparent quaternary InGaAlAs waveguide with an asymmetric InGaAs absorbing layer and the top cladding layer is realized from InAlAs. The waveguide structure, principle of operation and device layout are discussed in detail in [5]. With the fabricated prototype TW-PD an electrical output power of -11 dBm into a 50 Ω load has been generated (Fig. 2).

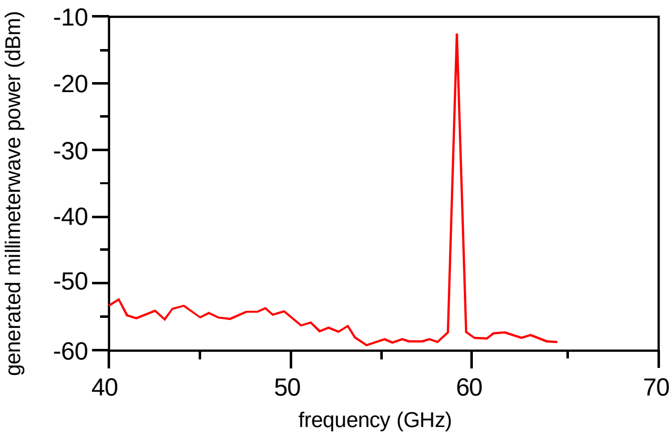

**Figure 2**: *60GHz output power of TW-PD.*

**High-speed waveguide electroabsorption modulators** – Besides the above mentioned receiver components, electro-optical modulators are the second key elements for an optical microwave transmission system. We have intensively studied waveguide EAM using again the concept of Fig. 1, i.e. an electrical coplanar waveguide and an optical waveguide. Physically, the quantum confined Stark effect (QCSE) has been used as the basic interaction mechanism. It has been shown that the fabricated EAM offer high-speed and broadband operation up to 70GHz, chirp control at mm-wave frequencies, high-sensitivity and the prospect for monolithic integration [6-8]. Moreover it should be pointed out, that the electroabsorption simultaneously leads to the generation of photocarriers, i.e. the EAM can also be used as a photodetector.

**Electroabsorption transceiver -** The dual-function modulator/photodetector to be discussed now is a high-speed electroabsorption (EA) waveguide device with a quaternary InGaAsP MQW core designed for polarization insensitive operation at 1.55µm. Efficient modulation and detection has been achieved simultaneously by employing a dual-lightwave technique [9,10]. In this approach, we operate the EA-transceiver (EAT) with two different wavelengths, one being adjusted for optimum modulation and the second wavelength for optimum detection performance. As a result the dual-lightwave/WDM technique enables full-duplex transmission with optimum device performance. Experimentally, the EAT exhibits a maximum extinction ratio and a minimum fiber-to-fiber insertion loss of 12dB and 7dB, respectively. Polarization dependence of the extinction ratio is less than 0.5dB and maximum optical input power is beyond 10dBm. For this device a remarkable responsivity in excess of 0.8A/W is found. The modulator and detecor performances of an EAT element are shown in Fig. 3.

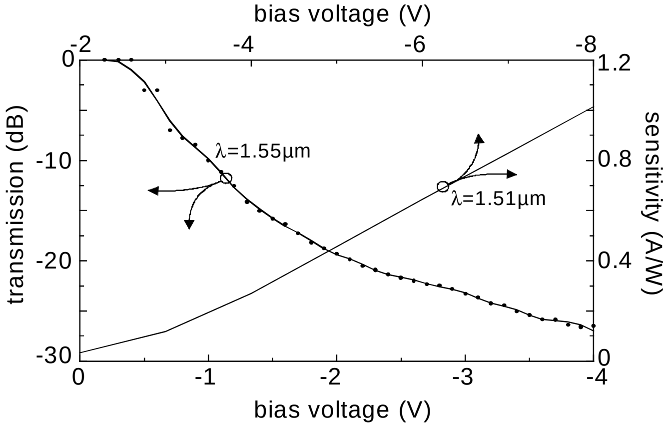


**Figure 3**: *Modulator and photodetector performance of EAT.*

**Millimeter-wave fiber-wireless transmission experiment** - The set-up for full-duplex 60GHz fiber-optic WDM transmission consists of a central station (CS) which is connected to a base station (BS) via non-dispersion shifted standard single mode fiber. Within the BS an EAT serves for simultaneous up- and downlink transmission [11,12]. (a) For downlink transmission, 156Mb/s DPSK data centered at an intermediate frequency (IF) of 2.6 GHz is upconverted to 59.6 GHz mm-wave frequency in the CS. The optical downlink carrier at 1.53µm is now intensity modulated with the mm-wave downlink signal and transmitted to the BS via the fiber. In the BS, the optical downlink signal is detected by the EAT downconverted to IF and demodulated in the mobile terminal (MT) to recover the 156Mb/s data and extract the clock signal. (b) For uplink transmission, 156Mb/s DPSK data centred at an IF of 3GHz is upconverted to 60GHz mm-wave frequency in the MT. The optical uplink carrier now at 1.56µm is intensity modulated with the mm-wave uplink signal by the EAT in the BS. The resulting optical uplink signal is then transmitted back to the CS, where it is detected, amplified, downconverted to IF and demodulated to recover the downlink data and clock. Experimental results on the link performance and error-free full-duplex point-to-point transmission will be presented.

**Fiber ring WDM network** - A network architecture for point-to-multipoint transmission is shown in Fig. 4. The network consists of a CS and an optical ring backbone that connects the cascaded BS each containing a single EAT. Wavelength routing in conjunction with optical add/drop multiplexing is employed to address each BS individually. As can be seen, the optical C-band (1.52-1.56µm) is used for downlink transmission and the L-band (1.57-1.61µm) for uplink transmission. Each C-band carrier is intensity modulated by the downlink data in the CS and multiplexed together with all L-band cw-carrier. A wideband erbium-doped fiber amplifier (EDFA) is used to amplify all channels simultaneously. Optical add/drop multiplexers (OADM) containing two fiber Bragg gratings in series are employed to drop the desired optical up- and downlink carrier to the dedicated BS, where the uplink carrier is being modulated with the uplink data. After the optical uplink carrier is added back into the fiber ring backbone by the OADM it is transmitted to the CS where the uplink data is recovered. Experimentally error-free full-duplex point-to-multipoint transmission has been achieved [13].

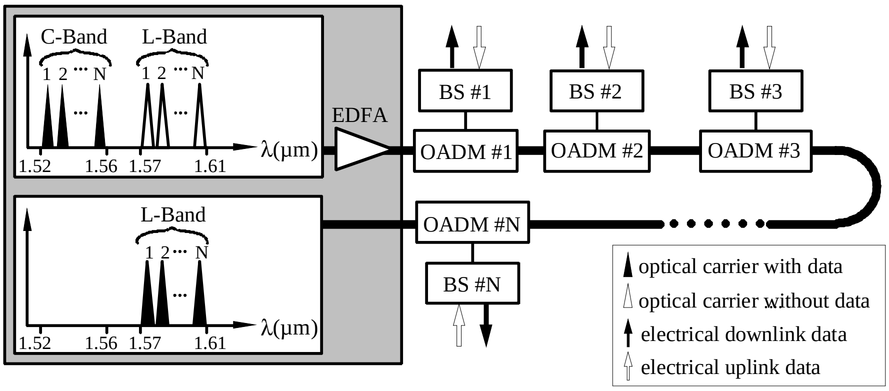


**Figure 4**: *60GHz fiber-wireless ring network*

**EMC optical microwave sensor** – A further application of microwave photonic devices is in the field of electrical field sensing. A schematic of the developed sensor system for the frequency range between 0.1 and 6GHz is shown in Fig. 5 [14]. Inside the sensor head an EAM is fed from a dipole antenna via a transimpedance amplifier. Due to the high sensitivity of the EAM the size of the field probe can drastically be reduced in comparison to commercially available E-field sensors. Furthermore an optical power supply is implemented into the sensor head to minimize the interference with the measured electric field by any electrical wiring.

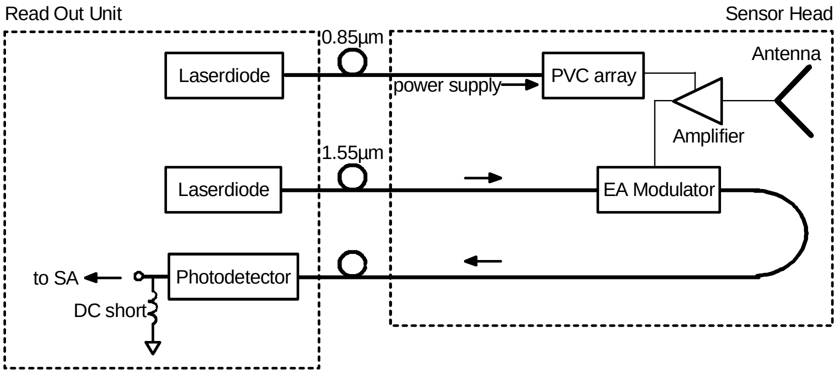

**Figure 5**: *Schematic of optically powered optical field sensor*

**Conclusion -** We presented a review on our recent work on high-speed photonic 1.55µm waveguide components and experimentally validated their applicability in microwave and mm-wave fiber-wireless networks. In detail, high-speed fiber-coupled 110GHz photomixer, 60GHz TW-PD, 70GHz EAM and 60GHz EAT have been presented. Full-duplex 156Mb/s transmission in a 60GHz fiber-wireless point-to-point link as well as in a ring network has been demonstrated and the application of an EAM inside a fiber coupled E-field sensor has been discussed.

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## References


[1] D. Jäger, "Microwave Photonics", in Optical Information Technology, ed. S.D. Smith and R.F. Neale, Springer-Verlag, 1993.

[2] International Topical Meeting on Microwave Photonics, Technical Digest, Duisburg 1997, Princeton 1998, Melbourne 1999.

[3] A. Stöhr, R. Heinzelmann, C. Kaczmarek, and D. Jäger, "Ultra Broadband $K_a$ to W-Band 1.55µm Travelling-Wave Photomixer", IEE Electron. Lett., (submitted).

[4] T. Alder, A. Stöhr, R. Heinzelmann, and D. Jäger, "High-Efficient Fiber-to-Chip Coupling using Low-Loss Tapered Single-Mode-Fiber", IEEE Photon. Technol. Lett., (submitted).

[5] M. Alles, U. Auer, F.-J. Tegude, D. Jäger "Distributed velocity-matched 1.55 µm InP travelling-wave photodetector for generation of high millimeter wave signal power", 1998 IEEE MTT-S International Microwave Symposium Digest, vol. 3, June 1998.

[6] O. Humbach, A. Stöhr, U. Auer, E.C. Larkins, J.D. Ralston, and D. Jäger, "Strained-Layer Multiple Quantum Well InGaAs/GaAs Waveguide Modulators Operating at 1µm", IEEE Photonics Technology Letters, vol. 5, no. 1, January 1993.

[7] P. Berini, A. Stöhr, D. Jäger, and K. Wu, "Rigorous MoL Modeling of Field-Induced Waveguides", IEEE/OSA J. of Lightwave Technology, vol. 14, no. 10, October 1996.

[8] A. Stöhr, K. Kitayama, and T. Kuri, "Fiber-Length Extension in an Optical 60GHz Transmission System Using an EA-Modulator with Negative Chirp", IEEE Photonics Technology Letters, vol. 11, no. 6, June 1999.

[9] A. Stöhr, K. Kitayama, and D. Jäger, "Error Free Full Duplex Optical WDM-FDM Transmission using an EA-Transceiver", International Topical Meeting on Microwave Photonics MWP'98, Princeton, October 1998.

[10] A. Stöhr, K. Kitayama, and D. Jäger, "Full-Duplex Fiber-Optic RF Subcarrier Transmission using a Dual-Function Modulator/Photodetector", IEEE Transactions on Microwave Theory and Techniques, vol. 47, no. 7, July 1999.

[11] T. Kuri, K. Kitayama, A. Stöhr, and Y. Ogawa, "Fiber-Optic Millimeter-Wave Downlink System Using 60GHz-Band External Modulation", IEEE/OSA J. of Lightwave Technology, vol. 17, no. 5, May 1999.

[12] A. Stöhr, T. Kuri, K. Kitayama, and D. Jäger, "Full-Duplex 60GHz mm-Wave Fiber-Optic Transmission", Electron. Lett., vol. 35, no. 19, Sep. 1999.

[13] R. Heinzelmann, T. Kuri, K. Kitayama, A. Stöhr, and D. Jäger, "Optical add-drop multiplexing of 60 GHz millimeterwave signals in a WDM radio-on-fiber ring", Optical Fiber Communication Conference OFC 2000, Baltimore, USA, March 2000

[14] R. Heinzelmann, A. Stöhr, M. Groß, D. Kalinowski, T. Alder, M. Schmidt, and D. Jäger, "Optically Powered Remote Optical Field Sensor System using an Electroabsorption-Modulator", 1998 IEEE MTT-S International Microwave Symposium Digest, vol. 3, June 1998.