Abstract - Microwave photonics can be generally defined as the study of high-speed photonic devices operating at microwave or millimeter wave frequencies and their use in microwave or photonic systems. In this multidisciplinary field at the interface between microwave techniques, ultra fast electronics and photonic technologies, typical investigations include, for example, high-speed and microwave signal generation, processing and conversion as well as the distribution and transmission of microwave signals via broadband optical links. From pioneering experiments in the 70’s, this field of microwave photonics has paved the way for an enabling novel technology with a number of commercially important applications. This paper is intended to give an overview on this multidisciplinary field of microwave and millimeter wave photonics.

I. INTRODUCTION
Within the last decade the field of microwave photonics has attracted growing interest worldwide. The term of microwave photonics was introduced in 1991 and used to describe novel optoelectronic components based upon the interaction of traveling optical and microwaves [1, 2]. In the following, the merging of microwave and photonic technologies was foreseen to be a new approach for future fiber radio communication systems where the RF signal is transmitted over optical carriers [3]. Since then the field of RF optoelectronics and photonics rapidly broadened: Since 1996 International Topical Meetings on Microwave Photonics (MWP) are being held annually [4] and 1995 was the first year of an IEEE MTT Special Issue on Microwave Photonics now being published regularly [5].

Microwave photonics [6] is an innovative multi- and interdisciplinary field combining and transferring different technologies. In particular, microwave technologies are used and employed in photonic and photonic technologies are utilized in microwave techniques. Moreover, in specific areas novel synergistic concepts have been developed by merging both technologies which particularly holds for the field of optoelectronics as their interface. As a result of ever increasing frequencies the term microwave stands here for GHz or THz frequencies in the frequency and equivalently for ps- or fs-time scales in the time domain.

This paper is intended to give an overview on this field of microwave photonics together with recent results ranging from devices and technologies to specific systems under investigation. In particular, the following topics will be addressed by way of key examples for the synergetic mixture of the two technologies involved: (i) Ultra fast photonic components such as optical modulators and detectors with special emphasis on traveling wave devices, (ii) Broadband analog optical links for high-speed interconnects, (iii) Microwave photonic systems based upon the merging of microwave and optical technologies.

II. MICROWAVE PHOTONIC COMPONENTS
For high-speed operation electronic devices are usually scaled down with respect to the lateral dimensions in order to decrease the device capacitance and to decrease the RC time constant. A solution of this problem is the use of propagation effects, i. e. to employ wave propagation phenomena in the design of the electronic device as has been described in [7] and already used in the design of high-speed integrated circuits such as RFICs and MMICs (cf. Traveling wave amplifiers). Moreover, at high frequencies the packaging of high-speed devices or circuits has basically to include wave propagation effects, for example the characteristic impedance of the electrical interconnect. Finally, the transit time and wave propagation effects of space charges have also to be regarded in the development of the high-speed device.

In optics on the other hand, wave propagation is the fundamental physical basis and no lumped elements exist up to now. As a consequence, the design of optical and photonic components usually includes optical waveguides and element dimensions large with respect to the wavelengths in optics.

(a)       (b)
Fig.1. Microwave optical interaction devices with vertical (a) and horizontal (b) light wave propagation.

In microwave photonic components an interaction between electrons, electrical fields and photons take place which can be regarded as microwave-optical interactions (Fig. 1). Consequently, different
technologies meet and may - in a synergetic mixture - be merged in order to develop novel concepts with great advantages. A key example is the traveling wave (TW) device (Fig. 2) where wave propagation effects in the electrical as well in the optical domain are utilized. The concept is based on the fundamentals of nonlinear optics where interaction takes place during wave propagation. Obviously, the bandwidths of these elements are not limited by „RC time constants“, see Fig. 3.

Fig.2. Traveling wave (TW) concept, [8, 9].

In an optoelectronic TW device [8, 9] an optical waveguide is used for optical wave propagation and an electrical transmission line (e.g. microstrip or coplanar waveguide) for guiding the microwave, usually in the same direction. In the region where the electrical fields overlap, the optoelectronic interaction occurs. Note that a dc bias may additionally be applied to control the operating point. From a physical point of view the interaction is a nonlinear or active process. The photodetector and the laser diode are basic examples of two-port devices where optical power is converted into electrical power and vice versa. Typical three-port devices are electrically controlled optical modulators/switches or optically controlled microwave modulators/switches. Due to the inherent nonlinearity these devices are further used for optoelectronic mixing of input electrical and/or optical signals where the output signal can be electrical or optical. For next generation broadband photonic communication networks, the electroabsorption modulator (EAM) will be a key element because it can be used also as an electroabsorption detector (EAD). As a result, this element is a multifunctional device [8, 9] which has been called electroabsorption transceiver (EAT) because of its applications in full-duplex optical communication links [10]. An EAT can further be used to generate artificial optical nonlinearities such as optical bistability [11] which gives rise to switching, logic and memory effects and may be useful for multiple-GHz A/D conversion. In Fig. 3, a comparison is made between a lumped EAM and a TW EAD with comparable cross sections. As can be seen, the lumped element exhibits a RC time constant corresponding to about 10 GHz whereas the TW device shows a clear response beyond 160 GHz. Obviously, the use of microwave technologies can drastically improve the bandwidth of such photonic devices.

III. BROADBAND FIBER OPTICAL LINKS

An analog optical link consists of an optical transmission medium (preferably a fiber) and optoelectronic converters on both sides [12]. The great advantage is that due to the broadband low-loss transmission capability the optical fiber (see Fig. 4) can ideally be used to transmit microwave signals and therefore replace other lossy metallic waveguides, e.g. X-band WG or coax. Here different techniques have been explored. For example, on the transmitting side a cw laser diode and an external modulator (electrooptic or EAM) and on the receiving side an optoelectronic photodetector can be used. Besides the bandwidth a key parameter of such a link is the link loss which depends on the conversion efficiencies of the optoelectronic elements, the optical coupling efficiencies and the attenuation and dispersion of the transmission medium [9, 12]. Note that a link gain can easily be achieved when an optical amplifier (EDFA) and/or external modulators, preferably on both sides, are being used [9]. For high-speed and broadband operation the a. m. TW microwave photonic devices can successfully be employed.

Fig.3. Frequency response of a lumped and a TW device.

Fig.4. Propagation loss of different transmission media, SM = single mode and MM = multimode glass fiber.

For bidirectional communications, the link would require a duplication of the elements on both sides in order to provide uplink and downlink transmission. This is the conventional system architecture. In an advanced system the base station contains only one optoelectronic element, the transceiver, as realized by an EAT [10]. Given that due to the basic physical mechanisms the electrical bandwidth of the EAT is the same for the
detection and the modulation process, a bandwidth of more than 160 GHz can be achieved using an TW EAT.

IV. MICROWAVE PHOTONIC SYSTEMS

Broadband fiber optic links are regarded to be basic building blocks for different microwave systems.

(a) Photonic signal generation and local oscillators: Fig. 5 shows the concept of UWB signal generation using a microstrip resonator with an optoelectronic switch as an RF mirror integrated with a broadband antenna [13-15]. Further, mixing two optical wavelengths from two frequency locked lasers or a two mode laser in a photodetector emulates a microwave local oscillator where the difference frequency is photonically generated by heterodyne techniques (Fig. 6) and where wavelength tuning provides a bandwidth of several THz depending on the bandwidth of the detector [16, 17].

(b) EMC sensor: When the modulator at the end of a fiber is driven by an electrical input signal at the given position, the received optical signal can be used to measure the electrical signal quantitatively at the transmitter side and a field sensor results. Note that an electrical dc power required at the sensor side can also be transmitted optically by employing a photovoltaic cell at the receiver side [18].

(c) Optoelectronic testing: A microminiaturized modulator chip working in reflection mode and coupled to the end of a fiber can be applied to measure electrical fields in free space with high spatial resolution [19]. This is also the basic concept for contactless high-speed testing of integrated circuits, well-known as the electrooptic sampling principle of Fig. 7, [20, 21].

(d) Hybrid fiber-coax systems: In cable TV (CATV) the signals received from TV satellites can be converted into the optical domain and fed into a fiber to be transmitted over long distances with only small attenuation. The optical signals being transmitted are converted back into the electrical domain and guided to the costumer via coaxial cable.

(e) Fiber-radio systems: It is agreed that fiber-radio access [22] will provide a solution to the demands for a wireless connection to the costumer ("last or first mile problem"). For broadband services the frequencies are in the millimeter wave range. Such a concept is based upon an optical link between the central station (CS) and the base station (BS) in a pico cellular structure. Recently, 60 GHz fiber radio links have been demonstrated providing 155 Mbps using EAMs for half-duplex and EATs for full-duplex transmission in a WDM ring network [23]. Fig. 8 shows a novel architecture of a 60 GHz fiber-radio access system [23]. LD denotes a laser diode, PD a photodetector, and EAT-X an EAT − mixer. MT is the mobile terminal.
system using an EAT, (i) to generate the 57 GHz carrier frequency from LD1 and LD1’ where LD1 is directly modulated by the downlink IF signal at 2.6 GHz, and (ii) to mix the photonic LO signal directly with the IF signal. LD2 provides the uplink signal to be modulated at the BS with the uplink signal.

(f) Antenna systems: A major application of optical link technology is the remoting of antenna systems and, particularly, the optical control of array antennas, see for example Refs. [4] and [5]. A millimeter wave or THz camera with photonic interconnection is foreseen.

V. CONCLUSIONS

In the past decade the field of microwave and millimeter wave photonics has become a key technology extending from components and modules to systems with important applications. The driver has been twofold: On one hand the broadband low-loss and high-speed transmission capability of optical fibers has led to a considerable interest in their use for distributing and controlling micro- and millimeter wave signals. On the other hand the breakthrough in the design and demonstration of several ultra-broadband photonic components has paved the way for wideband and high efficiency optoelectronic converters being important building blocks for microwave optical links. As a result, it can be foreseen that this multidisciplinary field of microwave photonics will continuously be expanded and lead to further novel concepts due to the synergetic merging of different technologies as has been done similarly in the area of MEMS, for example.

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