Microwave Photonics: Past, Present and Future

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***Abstract*—In this paper we highlight some of the notable advances in microwave photonics over the last ~ 45 years and present some speculations about where we may go in the future. Some personal reminiscences are also included.**

I. INTRODUCTION

The field that is now generally referred to as microwave photonics has been under active investigation for more than a quarter of a century and has roots that go back almost half a century. In the last two years there have been two reviews of the field [1, 2]. Our presentation here makes no attempt to be comprehensive. Rather we will highlight some of what, from our perspective, were the notable advances, and intersperse them with some personal reminiscences. Working day-to-day in this field it is sometimes difficult to see the progress one is making. However, when viewed from the perspective of more than a quarter century, the progress has been truly remarkable. This is what is covered in the past and present sections. But despite all the remarkable progress there is still much to be done. In the future section, we venture a glimpse at what may lie ahead..

II. THE PAST

A. *Early Devices*

Shortly after the development of the first diode laser by three independent groups of researchers in 1962 [3 – 5], it was used to construct an analog, free-space optical link. The modulation bandwidth of diode lasers was limited to a few megahertz, which correspondingly limited the link bandwidth.

The integrated optic version of a Mach-Zehnder interferometer was fabricated in lithium niobate back in 1975 [6]. Just a few years after that, papers began to emerge that investigated the possibility of using such modulators for analog modulation (see for example [7, 8]).

The “good” news was that reasonably good linearity could be obtained from either direct or external (sometimes referred to in the early literature as indirect) modulation. The “bad” news was that other performance parameters, such as link gain and noise figure, were miserable: the intrinsic link gain was ~ -50 dB and the noise figure was ~ 60 dB!

The predominant wavelength at the time, 0.8 μm, which corresponded to the emission wavelength of GaAs lasers, was not optimal for fiber attenuation or dispersion. Further, even 50 μW of 0.8 μm optical power caused photorefractive drift in lithium niobate.

B. *Early Applications*

The low loss of optical fibers, relative to coaxial cables, led to early attempts at using optical fibers as the basis for generating the delays required in true time delay beamformers for phased array antennas. An early system demonstration of microwave photonic links and time delays was reported by Hughes [9].

There was also early work on photonic replacements for many of the key RF components: a frequency down-converting link to replace an RF mixer [10] as well as a parallel array of Mach-Zehnder modulators with a binary progression of electrode lengths to perform A/D conversion [11]. However, until one achieved links with sufficiently good performance, it was hard to make a credible case for building photonic replacements for other RF devices.

The principal early commercial application of microwave photonics was to the distribution of cable TV (CATV) signals, which were analog. Using analog fiber-optic links – rather than digital links – simplified the hardware needed in the set-top cable box [12]. A key advance during this period was the development of distributed feedback (DFB) lasers that had sufficient performance to meet CATV needs.

Link design was largely what may be termed naïve link design: one typically took components with sufficient bandwidth and connected them into a link. If the resulting RF performance was lacking, RF amplifiers were added to reduce the link loss and noise figure.

Most (all?) microwave photonic hardware used in real applications (i.e. outside a laboratory environment) was based on individual devices (lasers, modulators, photodiodes, etc.). There was only a handful of work on integration (see for example Leheny [13] and Yariv [14]).

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III. THE PRESENT

Link performance has improved dramatically in all of the key performance metrics: bandwidth, gain, noise figure and spur-free dynamic range. Direct modulation of a diode laser has been reported up to 40 GHz [15], external modulation up to 110 GHz [16], link gains as high as 17.0 dB and noise figures as low as 5.7 dB have been reported at 12 GHz [17]. A variety of link linearization methods have been investigated resulting in spur-free dynamic ranges as high as 134 dB in a 1 Hz resolution bandwidth (albeit at low frequency: 150 MHz) [18].

The variety of photonic replacements for electronic components has expanded to include photonic oscillators [19], and development continues on photonic A/D converters [20] and photonic down-converting links [21].

The incremental modeling approach to link design has largely replaced naïve link design. Although links with intrinsic gain now are commonly accepted, the initial reaction was far less receptive. The first author recalls a comment that was made after presenting an early paper in which a link with positive intrinsic gain was reported: “The only thing I do not understand about your result is how an institution with the reputation of MIT let you talk about something that is so obviously wrong.”

Commercial microwave photonic links based on electro-absorption modulation are now also available [22], in addition to Mach-Zehnder-based external modulation and diode-laser-based direct modulation links.

Record-setting results are still largely (exclusively?) achieved with discrete photonic components. However, photonic integration has progressed to the point that initial commercial products are available, albeit primarily in the digital area [23].

IV. THE FUTURE

A. Volume Production

Photonics has reached the level where key parts are manufactured in reasonable volumes. Take for example 10-Gb modulators in lithium niobate, as representative of a “high” volume photonic part today. To support the world-wide market for these devices probably requires ~ 25 4”-wafer starts per day or about 300 in^2/day [24].

However, to put this in perspective, consider a “high” volume electronics part, such as the processor for electronic games. To meet this demand requires ~ 300 12”-wafer starts per day, which corresponds to ~ 34,000 in^2/day [25]!

Hence if photonics is to move into mainstream applications, we in the photonics community need to think of ways of producing these parts in orders-of-magnitude higher-volume, lower-cost ways. For example the cost of packaging in general, and fiber attachment in particular, often dominates the price of a photonic part. The packages are typically metal (often expensive metal alloys such as Kovar) and the fibers are hand attached. Compare this to electronic parts that are in plastic packages with wires attached via automated wire bonders.

B. Integration

Although it was recognized early on that integration would play an important role in the development of microwave photonics [13, 14], the development of integration is just now beginning to become widespread.

The reason for this has been the need to address several formidable challenges. One is the material challenge, since at present the principal microwave photonic devices – lasers, modulators, optical amplifiers and photodiodes – are fabricated in completely different materials – indium phosphide, lithium niobate, erbium-doped glass and indium gallium arsenide, respectively.

The other principal challenge is the need not only to integrate optical devices, but also in many cases to integrate optical devices with electronic devices. Further, unlike electronics where typically one is integrating multiple copies of the same device (think memory chips), in photonics one is faced with integrating very different devices (think laser and modulator).

Integration of optics: for this type of integration the material system will be largely determined by the wavelength of the application. Hence integration of fiber communication components would likely be done in the indium phosphide system, whereas applications at longer or shorter wavelengths would be integrated in materials with bandgaps appropriate for those wavebands.

Integration of optics with electronics: for this type of integration, the enormous momentum behind silicon means that this type of integration will have to be in silicon. In turn this implies that we must find ways to implement optical devices – both active and passive – in silicon. Progress along this path is already well underway.

SUMMARY

Microwave photonics is emerging from its “germanium” era. By that we mean that microwave photonics has made it through a round of development and reached its first level of widespread, commercial applications largely on the basis of individual devices. In an evolutionary sense this is analogous to where solid-state electronics was when germanium was the dominant electronic material: this was the first material for solid state electronics that achieved relatively widespread (at least for that time) commercial application based on individual electronic devices (i.e., there were no germanium integrated circuits).

As we look to the future of microwave photonics, the next stage in this field's evolution will be to enter an era analogous to the use of silicon in electronics: theoretical and device development will continue but commercial applications will be based largely on integrated rather than individual devices.

ACKNOWLEDGMENT

The authors would like to thank the other members of the PSI staff for their helpful suggestions: Gary Betts, Bill Burns, Alan Chen, Mary Phillips and Joelle Prince.

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