Niels Neumann

Microwave Photonic Applications - From Chip Level to System Level

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Microwave Photonic Applications – From Chip Level to System Level

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Abstract

The hybridization between microwave and optical technologies – microwave photonics – is an emerging field with high potential. Benefitting from the best of both worlds, microwave photonics has many use cases and is just at the beginning of its success story. The availability of a higher degree of integration and new technologies such as silicon photonics paves the way for new concepts, new components and new applications.

In this work, first, the necessary basic building blocks – optical source, electro-optical conversion, transmission medium and opto-electrical conversion – are introduced. With the help of specific application examples ranging from chip level to system level, the electro-optical co-design process for microwave photonic systems is illustrated. Finally, future directions such as the support of electrical carriers in the millimeter wave and THz range and realization options in integrated optics and nanophotonics are discussed.

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Nomenclature

AC .... Alternating Current
AGC .... Automatic Gain Control
APD .... Avalance Photodiode
ASK .... Amplitude Shift Keying
BER .... Bit-Error Rate
BS .... Base Station
CPU .... Central Processing Unit
CS .... Central Station
CW .... Continuous Wave
DBR .... Distributed Bragg-Reflector
DC .... Direct Current
DFB .... Distriubuted Feedback Laser
DGD .... Differential Group Delay
DNA .... Deoxyribonucleic acid
DP-QPSK ..... Dual Polarization Quarternary Phase Shift Keying
DPMZM ...... Dual Parallel Mach-Zehnder Modulator
DSB .... Double Side-Band
DWDM .... Dense Wavelength Division Multiplex
E/O .... electro-optical
ECL .... External Cavity Laser
EDFA .... Erbium Doped Fiber Amplifier
EPIC .... Electronic-Photonic Integrated Circuit
ESA .... Electrical Spectrum Analyzer
FBG .... Fiber Bragg Grating
FTTA .... Fiber-to-the-Antenna
FWHM .... Full Width at Half Maximum
FWM .... Four-Wave Mixing
HD .... High Definition
HPBW .... Half Power Beam Width
HPC .... High Performance Computing
IC .... Integrated Circuit
IF .... Intermediate Frequency
IL .... Insertion Loss
IQ .... Inphase and Quadrature
ISM .... Industrial, Scientific and Medical
LAN .... Local Area Network
LDD .... Laser Diode Driver

LED .... Light-Emitting Diode
LF .... Low Frequency
LNA .... Low-Noise Amplifier
LO .... Local Oscillator
LPG .... Long-Period Grating
MDM .... Mode Division Multiplex
MIMO .... Multiple Input Multiple Output
MMF .... Multi-Mode Fiber
mPSK .... m-ary Phase Shift Keying
mQAM .... m-ary Quadrature Amplitude Modulation
MS .... Mobile Station
MUX .... Multiplexer
MZI .... Mach-Zehnder Interferometer
MZM .... Mach-Zehnder Modulator
NOC .... Network on Chip
NRZ .... Non-Return to Zero
O/E .... opto-electrical
OAM .... Optical Angular Momentum
ODSB-SC ..... Optical Double Side-Band modulation with Suppressed Carrier
OFDM .... Orthogonal Frequency Division Multiplexing
OFDR .... Optical Frequency Domain Reflectometry
OM3 .... Optical Multi-Mode Fiber, Class 3
OOK .... On-Off Keying
OSA .... Optical Spectrum Analyzer
OTA .... Over-the-Air
PCB .... Printed-Circuit Board
PE .... Polyethylene
PIC .... Photonic Integrated Circuit
PMD .... Polarization Mode Dispersion
QPSK .... Quadrature / Quaternary Phase Shift Keying
RAU .... Remote Antenna Unit
RF .... Radio Frequency
RIN .... Relative Intensity Noise
RMS .... Root Mean Square
RoF .... Radio-over-Fiber
ROP .... Received Optical Power
RRH .... Remote Radio Head
Rx .... Receiver
RZ .... Return to Zero
SBS .... Stimulated Brillouin Scattering
SDM .... Spatial Division Multiplex
SMA .... Sub-Miniature version A
SMF .... Single-Mode Fiber
SMSR .... Side-Mode Suppression Ratio

SNR .... Signal-to-Noise Ratio
SOI .... Silicon-on-Insulator
SPM .... Self-Phase Modulation
SPR .... Surface-Plasmon Resonance
SRS .... Stimulated Raman Scattering
SSB .... Single Side-Band
TE .... Transverse Electric
TIA .... Trans-Impedance Amplifier
TM .... Transverse Magnetic
TSV .... Through Silicon Via / Through Substrate Via
TTD .... True Time Delay
Tx .... Transmitter
UWB .... Ultra Wide-Band
VCSEL .... Vertical Cavity Surface-Emitting Laser
VOA .... Variable Optical Attenuator
WDM .... Wavelength Division Multiplex
XPM .... Cross-Phase Modulation

1 Introduction

The invention of the semiconductor laser[1] was the nucleus for optical communication systems to replace their electrical counterparts. The use of light as carrier has some major advantages over traditional electrical systems. In optical domain, there is nearly unlimited bandwidth available. One major application is the transmission of enormous amounts of data over long distance with low loss. Additionally, the optical signal can be modified and transformed (e.g. generating electrical carriers, filtering and sensing). However, information processing and memory are still realized in electrical domain.

Wireless RF signals are advantageous in lots of applications. That means, efficient electro-optical and opto-electrical conversion is needed when used together with optical transmission. Achieving the best system performance requires a careful balance of electrical and optical parts. This is not possible without a proficient co-design of optical and RF building blocks, the field of microwave photonics. This work contributes to the growing interest in that kind of systems. From chip-level with distances in the micrometer range over board-level applications (centimeter) to access systems spanning over kilometers, microwave photonic solutions can be found benefitting from the heritage in data center and backbone communication systems.

Long-haul systems are operated in the second (at 1.3 μm wavelength) and third optical window at a wavelength of about 1.5 μm. Single-mode silica fibers ensure maximum performance. Linear (chromatic dispersion, polarization mode dispersion and attenuation) as well as nonlinear effects impair the transmitted signal. In the second optical window, the chromatic dispersion has its minimum for standard single-mode fiber while the third optical window is located at the attenuation minimum. Not only is mode dispersion avoided by the single-mode operation but also devices based on mode coupling such as gratings can be conveniently used. Among other applications, this enables sharp filters for dense wavelength division multiplexing (DWDM).

Data centers set completely different demands: Transmission distances stay well below 10 km but connectivity is crucial. Requirements for signal distortions are relaxed so that multi-mode fibers can be used. Connector technology can be more cost-effective and simpler due to lower needs for mechanical precision because of the bigger fiber diameters. Data center systems usually work in the first optical window at 850 nm wavelength. They are designed in an economical way with a lower accumulated data rate per fiber. That's because of working with lower line rates and less spectrally efficient modulation formats. Moreover, only a small number of WDM channels are used.

Expanding into smaller and smaller transmission distances, optical systems face multiple constraints when serving for chip-to-chip and on-chip applications. While

[1] an acronym for "light amplification by stimulated emission of radiation"

the board-to-board communication and on-board systems have been influenced by the data center based paradigm (multi-mode waveguides and low spectral efficiency), the chip-level feature sizes impose single-mode waveguides. Silicon as omnipresent material can be used as waveguide material for wavelengths larger than 1 μm. However, in the silicon photonics scenario, the light source is one of the major challenges. Silicon is an indirect bandgap material. That makes it a big challenge to build an efficient silicon based laser. Hence, mostly external III-V lasers are used nowadays. In order to include lasing functionality to silicon based chip technology, multiple approaches are followed to integrate III-V technology to silicon substrates for wafer-level manufacturing. Thick buffers grown between Si and InGaAs help to adjust the lattice mismatch and decrease the number of crystalline defects. A costly alternative is the direct wafer bonding.

The use of optical waveguides such as fibers limits the optical systems to static or quasi-static applications. Linking them with wireless technology overcomes this drawback and allows reconfigurable and portable solutions. Mobile connectivity is the main cause for growth rates in terms of bandwidth and number of devices. However, only the last meters from the base station to the mobile unit are transmitted over the air. The rest of the network is realized largely in optical domain in order to meet the challenging performance demands. Microwave photonic technologies such as carrier generation, electro-optical conversion and signal processing using photonics can be used to simplify the network design. Moreover, for shorter distances (e.g. for board-to-board communication), wireless approaches like beam steering / beam switching can be applied to adaptively distribute a data stream to many different locations. This kind of large-scale integration between optical and radio techniques is only possible with microwave photonics.

In this work, important aspects of microwave photonic systems are studied in showcase scenarios. First, the required building blocks are briefly introduced in chapter 2. The implications of applying the well-known parts liker lasers, modulation, typical transmission media and opto-electrical conversion in the context of microwave photonics are discussed. Following, the broad field where microwave photonic systems can be deployed is illustrated with the help of examples for chip-level, board level and system level operation in chapter 3. These examples cover ultra-short transmission distances from a few hundred micrometers (through silicon vias) to tens of kilometers (Radio-over-Fiber systems). At the same time, the different options of using the optical medium just for transmission (chip-level intraconnects), to connect photonics seamlessly with wireless technology (fiber-to-the-antenna), to introduce photonic RF generation (with Talbot effect and in the Radio-over-Fiber system) or to attach an electrical read-out to optical sensors in order to enhance the fields of application are presented. Finally, the outlook in chapter 4 describes how to push microwave photonics to higher frequencies in the THz region and to smaller scales in nanophotonics.