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Introduction to Microwave Photonics

In the realm of modern information and communications, the demand for high-speed, highly secure, and reliable systems is ever-increasing. As a result, researchers and engineers are constantly exploring novel solutions to transmit and manipulate data at higher speeds and higher frequencies. Microwave photonics has emerged as a promising interdisciplinary field that combines the advantages of photonics and microwave engineering to overcome the limitations of traditional electronic systems. Microwave photonics is a field that encompasses the interaction of microwave and optical waves and leverages the inherent advantages of both domains to achieve enhanced system performance in terms of bandwidth, speed, signal quality, and energy efficiency. In essence, microwave photonics aims to bridge the gap between optics and microwaves by utilizing optical techniques to generate, process, control, and distribute microwave signals. This book explores the fundamentals of microwave photonics including photonic generation, processing, control, and distribution of microwave signals or waveforms. Specifically, the book covers the following key concepts and techniques.

1.1 Photonic Generation of Microwave Signals

Photonic generation of microwave signals refers to the use of photonic techniques for the generation of microwave signals. There are two major approaches to generating a microwave signal, including heterodyne detection of two coherent optical waves at a photodetector in which the two coherent optical waves can be generated by either using a dual-wavelength laser source or through optical modulation, and the use of an optoelectronic oscillator (OEO). Photonic RF generation is particularly useful in applications where high-frequency signals need to be generated with excellent performance in terms of stability, phase noise, and frequency agility. Photonic microwave generation offers several advantages over traditional electronic microwave generation techniques. It can provide wide bandwidth, low phase noise, high-frequency resolution, and immunity to electromagnetic interference (EMI). It also allows for integration with other photonic components, enabling compact and efficient microwave systems.

1.2 Photonic Microwave Signal Processing

Microwave photonic filters are essential devices for photonic microwave signal processing. Microwave photonic filters are implemented by a combination of microwave and photonic technologies to achieve various filtering functions. The filters utilize the advantages of photonic systems,

such as wide bandwidth, low loss, and high-speed signal processing. In a microwave photonic filter, the microwave signal is converted into an optical signal, processed using photonic techniques, and then converted back to the microwave domain. This approach allows for the implementation of advanced filtering functions with improved performance compared to conventional electronic filters such as wider bandwidth, higher selectivity, lower loss, and better tunability. In addition, photonic implementation has an added advantage by processing high-frequency and wideband microwave signals without suffering from EMI. These advantages make them suitable for applications in radar and wireless communications systems.

1.3 Photonic Distribution of Microwave Signals

Photonic distribution of microwave signals is implemented by microwave photonic links. A microwave photonic link, also known as analog photonic link, is a technology that combines microwave and photonic technologies to enable the transmission of wideband and high-frequency microwave signals over an optical fiber. In a microwave photonic link, the microwave signal (usually digital data modulated on a microwave carrier) is converted into an optical signal using an electro-optic modulator (EOM) such as a Mach–Zehnder modulator (MZM) or a phase modulator (PM). The EOM imposes the microwave signal onto an optical carrier, which is transmitted over an optical fiber at an ultra-low loss. At the receiving end, the optical signal is converted back into a microwave signal at a photodetector (PD). The use of optical fibers in microwave communications offers several benefits. First, optical fibers have a much wider bandwidth compared to traditional copper cables, allowing for the transmission of wideband microwave signals. Second, optical fibers have much lower loss compared to traditional copper cables, allowing for the transmission over a long distance. In addition, optical fibers are immune to EMI, a feature that is absent in copper cables and is extremely important when being used in an electromagnetic complex environment. This makes microwave photonic links ideal for applications where high-speed, long distance, and high-quality microwave transmission is required, such as in wireless communications systems, radar systems, and satellite communication systems.

1.4 Photonic Generation of Ultra-wideband Signals

Photonic generation of Ultra-wideband (UWB) signals is a technology to use photonic techniques to generate UWB signals thanks to the ultra-wide bandwidth offered by modern photonics. The FCC has allocated a specific frequency range for UWB operations in the US from 3.1 to 10.6 GHz with a power spectral density (PSD) defined to prevent interference with other wireless services. The photonic generation of UWB signals offers several advantages including large bandwidths, high data rates, and low power consumption. In addition, the inherent characteristics of UWB, such as resistance to multipath fading and precise ranging capabilities, can be combined with the benefits of optical communication systems. Applications of photonic UWB signals include wireless communications, ranging and localization systems, radar imaging, and high-resolution sensing. By leveraging the capabilities of both photonics and UWB, these systems can achieve advanced performance in terms of high-speed data transfer, high positioning accuracy, and high imaging resolution.

1.5 Photonic Generation of Microwave Arbitrary Waveforms

Photonic Arbitrary Waveform Generation (AWG) refers to the generation of arbitrary microwave waveforms using photonic techniques. It involves the use of optical components and devices to create complex waveforms in the optical domain with specified amplitude, frequency, and phase characteristics, and converted to the electrical domain at a photodetector. Photonic AWG provides several advantages, including wide bandwidth, fast processing speeds, and precise control over waveform parameters. Photonic arbitrary waveform generation can find applications in various fields, including optical communications, to generate complex waveforms with advanced modulation formats, signal processing, and optical signal shaping in optical communication systems; radar, to generate versatile waveforms for radar imaging, target detection, and signal processing. It also finds applications in sensing systems, such as optical coherence tomography (OCT), where precise waveform control is crucial. Photonic arbitrary waveform generation offers unique capabilities for creating customized waveforms with wide bandwidth, high accuracy, and large flexibility.

1.6 Microwave Photonic Beamforming Networks for Phased Array Antennas

Microwave photonic beamforming based on photonic true time delays is a technique used in phased array antenna systems to steer the beam of an antenna array by applying precise time delays to the microwave signal at each individual antenna element. It is commonly used in applications such as radar systems, wireless communications, and satellite communications. A phased array antenna system consists of an array of antenna elements arranged in an array or a grid pattern. Each antenna element can transmit and receive signals independently, enabling beam steering and forming of the radiation pattern. By controlling the time delays of the signals across the antenna elements, the main beam of the antenna array can be steered thanks to the constructive interference of the time delayed microwave signals at the far field, resulting in a focused beam in the desired direction. True time delay beamforming offers several unique advantages over conventional phase-shift-based beamforming techniques in terms wider instantaneous bandwidth and free of beam squint. True time delay can be implemented using photonic delay lines such as dispersive fibers, fiber Bragg gratings, and photonic integrated resonators such as ring resonators and microdisk resonators. True time delay phased array beamforming is a powerful technique which can find applications where squint-free microwave beamforming with wide instantaneous bandwidth is required.

1.7 Photonic-Assisted Instantaneous Microwave Frequency Measurements

Photonic-assisted microwave frequency measurements refer to the use of photonic techniques to perform measurements and analysis in the microwave frequency range. It involves the conversion of microwave signals into optical signals and the subsequent processing and analysis of these optical signals in the optical domain using various photonic devices, such as optical delay lines, fiber Bragg gratings, and dispersive elements. The field of microwave photonic measurements has gained significant research interest due to the advantages offered by photonics including high-frequency measurements, wide bandwidth, high sensitivity, and large dynamic range, which contribute to the

advancements in microwave signal and system characterization. The immunity to EMI of photonic systems is an added advantage of performing microwave measurements using photonics.

1.8 Microwave Photonic Sensors

Microwave photonic sensors are a class of sensors that utilize microwave photonic techniques to perform optical sensing in which the optical sensing information is translated to the microwave domain with much higher sensing sensitivity and precision. In a microwave photonic sensor, an optical sensing signal in which the sensing information is encoded as a frequency or wavelength change is converted to a microwave signal. By measuring the microwave frequency change, the sensing information is obtained. Since the frequency of a microwave signal is much lower than that of an optical signal, the sensing sensitivity and precision are significantly increased. In addition to the increased sensing sensitivity and precision, microwave photonic sensors have other advantages such as immunity to EMI and ability to achieve distributed and remote sensing. Microwave photonic sensors have found applications in various fields, including telecommunications, aerospace, defense, and civil engineering.

1.9 Photonic Analog-to-Digital Conversion

Photonic analog-to-digital conversion (ADC) is a technique that utilizes photonic techniques to convert analog signals into their digital representations. It leverages the advantages of photonics, such as wide bandwidth, high-speed processing, and immunity to EMI, to achieve high-performance ADCs with enhanced capabilities. The basic principle of photonic ADC involves the conversion of an analog signal into an optical signal, followed by the processing and digitization of the optical signal using photonic techniques. Some common approaches include (i) optical sampling ADC, to utilize ultrafast photonic sampling techniques to directly sample an analog signal at a very high sampling rate. The analog signal is first converted into an optical signal and then a train of optical pulses is used to sample the signal in the time domain. The optical samples are subsequently processed and digitized using electronic components; (ii) photonic time-stretch ADC, to time-stretch an analog signal in the time domain using a dispersive medium, and the time-stretched analog signal is then optically sampled and digitized using high-speed photodetectors and electronic ADCs. The time-stretching approach allows for slower electronic ADCs to be used, enabling higher resolution and improved performance.

1.10 Novel Optoelectronic Oscillators

Novel OEOs refer to recently reported OEO schemes that overcome the limitations of traditional OEOs. Novel OEOs have been widely investigated in the past few years, and a diversity of new insights and breakthroughs have been proposed and demonstrated. For instance, a novel microwave photonic iterative nonlinear gain model has been reported, which can be used to analyze different oscillation states of an OEO. A novel PT-symmetric OEO has been proposed and demonstrated by using PT symmetry for mode selection, where single-mode oscillation can be achieved without using any narrowband optical/electrical filters. Novel OEOs that are capable of producing complex microwave waveforms have been developed, including novel Fourier domain

mode-locked OEO for chirped signal generation, optoelectronic parametric oscillator for stable multi-mode oscillation, and broadband random OEO for random signal generation. Moreover, novel integrated OEOs featuring compact size and low power consumption have also been demonstrated, which are key steps toward a new generation of compact microwave sources for demanding applications.

1.11 Quantum Microwave Photonics

Quantum microwave photonics is to use quantum technology to improve the performance of classical microwave photonic systems. By combining microwave photonics and quantum technology, quantum microwave photonics can achieve features or functions that are very complex or even not possible using traditional microwave photonic or quantum technology. The key to the current quantum microwave photonic systems is the quantum single-photon detection scheme, which replaces the signal detection scheme in a traditional microwave photonic link to the quantum single-photon detection scheme. By doing so, the bandwidth and sensitivity limitations of a traditional microwave photonic system can be solved due to the wide processing bandwidth and high sensitivity of a quantum single-photon detection scheme. Quantum microwave photonic systems for weak microwave signal detection, RF phase shifting and filtering, nonlocal frequency-to-time mapping, RF compressed sensing, as well as quantum key distribution have been proposed and demonstrated in recent years, which show clearly that quantum technology brings new opportunities to microwave photonics.

1.12 Integrated Microwave Photonics

Integrated microwave photonics (IMWP) is the study of the integration of photonic devices and microwave components on a single chip or substrate through monolithic or heterogeneous integration. IMWP systems typically consist of optical waveguides, which guide and manipulate light, a set of active and passive photonic devices, and microwave components. Active devices include lasers, modulators, and photodetectors, which generate, modulate, and detect optical signals, respectively. Passive devices include optical couplers, optical filters (resonators), and optical delay lines, which route and process the optical signals. Microwave components include amplifiers and electronic couplers. The most important materials used for photonic integration include InP, Silicon, Silicon Nitride, and Lithium Niobate. Among them, silicon is being heavily studied thanks to its unique feature of compatibility with the mature CMOS technology, to leverage existing infrastructure and manufacturing processes of the semiconductor industry, allowing for cost-effective and scalable production of photonic devices. However, silicon is a non-direct bandgap material, which cannot produce light amplification and lasing. To have a fully integrated system, a light source is always needed. A solution is to implement hybrid integration, by integrating InP-based light sources on a silicon substrate.

1.13 Applications of Microwave Photonics

Microwave photonics has numerous applications in telecommunications systems, radar and sensing systems, radio astronomy, and biomedical imaging. For telecommunications systems, it enables the transmission of wide-bandwidth microwave signals over optical fibers, significantly

extending the communications distance for wireless systems. In addition, microwave photonics enables the integration of wireless and optical networks, facilitating seamless connectivity and improved network performance. In radar and sensing systems, microwave photonics enhances radar capabilities by enabling the processing and distribution of microwave signals with higher frequency and wider bandwidth. It also enables the integration of multiple radar systems, improving the efficiency and accuracy of surveillance and sensing applications. In radio astronomy, radio telescopes use microwave photonics to capture and analyze radio frequency signals from celestial objects. The high-frequency stability, accuracy, and wide bandwidth of microwave photonics enable precise measurements and imaging of distant stars, galaxies, and cosmic microwave background radiation, and finally, in biomedical imaging, microwave photonics has potential applications in biomedical imaging techniques, such as microwave tomography and microwave-induced thermoacoustic imaging. These techniques leverage the unique properties of microwave signals to create detailed images of biological tissues, aiding in medical diagnostics and treatment planning.