High-resolution Microwave Photonics Using Strong On-chip Brillouin Scattering

Amol Choudhary
Department of Electrical Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
Author e-mail address: achoudhary@ee.iitd.ac.in

Abstract: Processing of microwave signals with resolution as low as 10 MHz is enabled by integrated Brillouin scattering with gain >50dB. We discuss reconfigurable filters, delay lines and phase shifters and also focus on system performance.

1. Introduction

Photonic processing of microwave signals has become critical for several demanding wireless communications applications requiring large instantaneous bandwidths and a high degree of reconfigurability. With the imminent roll-out of the 5G infrastructure, microwave photonics will play a key role in radio over fiber (RoF) links, and beamforming of RF signals which is a critical component of the Massive Multiple Input Multiple Output (MIMO) architecture [1]. Furthermore, the large frequency ranges that can be offered by integrated microwave photonics (MWP) [2] is perfectly suited to serve the >25 GHz frequency bands required by these networks.

While MWP has made some considerable advances in the areas of signal generation and signal transport, with several products and field deployments, functional MWP circuits have not yet made it out of the laboratories to the communication networks. There are some underlying reasons for this: firstly, complete large-scale integration of microwave photonic devices is not yet at a maturity level where the devices can compete with traditional RF devices. Recently, integration of several photonic circuits on a carrier board has enabled a beamforming network [3]. Secondly, the resolution of most photonic devices exceeds hundreds of MHz, making the processing of narrowband signals challenging. Thirdly, the system performance metrics: noise nigure (NF), link gain (G), spurious free dynamic range (SFDR), compression free dynamic range (CDR) are not comparable to what is offered by traditional RF electronics [4].

Stimulated Brillouin scattering (SBS) [5] has emerged as a key enabler to solve some of these challenges. SBS is a nonlinear three-wave interaction of two counter-propagating optical waves (pump and probe) and an acoustic wave that leads to narrowband gain (loss) on the probe signal at a lower (higher) frequency than the pump wave. This narrowband (~30 MHz) gain leads to a sharp phase response, and thus a large delay. Over the last decade, on-chip SBS [5-8] has emerged as an important technology for achieving MWP functionalities [9-11] to bridge high-resolution RF signal processing and coarse signal processing with several demonstrations of on-chip MWP filters, phase shifters, and delay lines being demonstrated.

In this paper, the functionalization of MWP links using SBS is discussed and the recent progress in the field of SBS-based MWP functionalities enabled due to large on-chip SBS gains of >50 dB is presented. Some efforts to understand and optimize the RF performance metrics of such devices, and a pathway for making such devices practical for field deployment are outlined.

2. On-chip Brillouin Processing of Microwave Signals

A typical integrated microwave photonic functionality [2] consists of a laser, on which the RF signal is encoded using electro-optic modulation, thus upconverting the RF signal to optical frequencies. An optical processor (on-chip SBS for high-resolution signal processing, for example) is introduced after the modulator which provides the desired MWP functionality following which a square law photodetector down-converts the optical signal to the RF domain. In addition to choosing the best-suited optical processor, it is critical to also choose the modulator carefully. There are several choices of modulation [12]: phase modulation (PM), dual sideband (DSB) modulation achieved using an intensity modulator, single sideband (SSB) modulation achieved using an intensity modulator with sideband filtering or using a dual drive Mach Zehnder Modulator (MZM) or a dual parallel MZM (DPMZM). In addition to these well-known modulation techniques, arbitrary modulation technique (AMT) [11] can also be used, where both sidebands can have arbitrary amplitudes and phase enabling advanced RF photonic functionalities.

Recently, large on-chip SBS gains of up to 50 dB [13] have been achieved in a chalcogenide platform by using waveguides with small mode areas of ~1.5 μm^2, propagation losses of <0.5 dB/cm and long propagation lengths of ~24 cm. This large gain has release the bottlenecks previously faced by SBS-based MWP, thereby unlocking new functionalities. This is because, if we consider the amplitude response of SBS, the gain maps 1:1 to RF filter selectivity if SSB [11] is used. While, if we consider the phase response, a larger gain results in a larger phase shift and hence a larger delay [10]. Combining this high on-chip SBS gain with carefully engineered systems utilizing various modulation techniques enables advanced MWP functionalities. A commonly employed technique is known as RF interference [14], where additional control signals are added in the optical domain on one sideband, with the RF information being encoded on the other sidebands. Both the sidebands have a controllable phase difference between them, leading to interference in the RF domain upon photodetection.

3. Brillouin RF photonic functionalities

3.1 Bandpass Filter

In principle, a 50-dB SBS gain results in a narrow bandpass (10 MHz) filter with 50 dB selectivity [13] or if using SBS loss (the Anti-Stokes response), a notch filter [11] with 50 dB rejection. It is also possible to tailor the SBS gain, to effectively 'spread' the gain over a larger bandwidth. This can be done using multiple electrical lines that can be modulated into the optical domain, thus creating a comb of pump lines which results in highly reconfigurable SBS responses and thus highly reconfigurable RF filters [15, 16]. By taking advantage of RF interference, the selectivity and rejection of bandpass and stopband filters can be improved, respectively. Combining high SBS gain with gain tailoring and RF interference, bandpass filters that are tunable from 30MHz - 440 MHz [15], multi-band filters [15] and bandstop filters [16] tunable from 18 MHz - 300 MHz have been realized.

3.2 EIT-like MWP processor

A narrowband filter based on SBS has also been demonstrated, where two loss responses were synthesized on the tail of a gain response thus reducing the filter bandwidth. Combining this response with RF interference, leads to filter profiles with an 'Electromagnetically Induced Transparence (EIT)-like' shape with high selectivity [17]. These filter profiles are also widely tunable in frequency and in bandwidth, with a bandwidth reduction of ~2 being achieved. The phase response on the sideband exhibits a vector-addition-induced phase amplification [10] by almost an order of magnitude when compared to without the use of RF interference. Finally, a pulse delay experiment was carried out where a pulse delay of 2.4 ns showing a factor of 6 improvement in the delay when compared to without the use of RF interference was demonstrated.

3.3 True Time Delay

In the case when the signal bandwidths are comparable to the carrier frequency, beamforming networks are evolving towards the use of true time delay (TTD) lines to avoid beam squinting. This can be achieved using an MWP technique known as separate carrier tuning, where a time delay is imparted to the sideband, and a phase shift is introduced on the optical carrier. Large SBS gain becomes critical in this case, since a broadened delay is added to the sideband, and a tunable phase shift is imparted to the carrier, both processes requiring optical power to pump the SBS gain medium. This was achieved using a chip with 47 dB net SBS gain [18]. This technique can be combined with the RF interference technique in the future to enable low-power TTD lines.

3.4 Broadband phase shifter

A broadband phase shifter can be achieved by imparting a phase shift on the carrier using SBS. However, a phase shift of only 240° was achieved using this technique due to the limited available SBS gain [19]. This has been a long-standing problem in the field and was somewhat alleviated using 47 dB on-chip SBS gain, however a full 360° phase shift could not be achieved [18]. More recently, forward SBS in silicon was harnessed to achieve a 360° phase shifter operating up to 20 GHz using RF interference with a phase amplification of a factor of 25 [20]. This is a useful technique to reduce the power consumption of Brillouin-based broadband phase shifters.

4. System Performance

One of the perceived challenges of integrated MWP are the system performance metrics and there has been recent efforts to overcome them [4]. An optimized notch filter was also demonstrated which combined linear and nonlinear elements on a photonic chip [21]. A ring resonator was cascaded with on-chip SBS in a chalcogenide waveguide, and this circuit was deployed in a high-performance MWP link. The ring resonator provided a sharp phase response, which goes through π (at the filter's center frequency) on one sideband. The SBS compensates for the dip in the transmission response of the ring. This configuration approximates a phase-only filter which imparts a π-phase only at the filter frequency. Through destructive interference, this results in a notch filter with a rejection = 40 dB and was tunable by 9 GHz. The performance metrics were: G= −10 dB, NF= 27 dB, and $SFDR_3$= 96 dB $Hz^{2/3}$. In this case the SBS noise was added in the stop band and did not distort the signal of interest.

To understand the effect of SBS-based MWP devices in a bandpass configuration, a systematic study has been recently [22] carried out to experimentally measure and to theoretically predict the NF, G, extinction ratio and resolution of filters using phase modulation (PM) and intensity modulation (IM). The SBS response was also switched between gain and loss. It was found that the lowest noise figure was achieved when SBS losses were used on both sides of the signal of interest to 'carve-out' a bandpass response using IM, while the best G was realized using SBS gain with IM. However, it should be noted that as the bandwidth of the filter reduces to 100 MHz, the NF of both cases becomes comparable and hence SBS gain with IM is best suited for high-resolution bandpass filtering.

5. Conclusions and Future Outlook

In this paper, we have presented challenges currently being faced by microwave photonics and have discussed how on-chip stimulated Brillouin scattering (SBS) can alleviate some of them. Recent advances in photonic fabrication, has enabled up to 50 dB of SBS gain from a chip-scale device, which has opened the door to many previously unattainable functionalities such as highly reconfigurable filters, 360° phase shifters, and true time delays. More recently, SBS has for the first time been used for high-capacity coherent optical communications, where narrowband SBS gain was used for the purification of an optical frequency comb-based transmitter [23]. Also, SBS was used at the receiver to extract a local oscillator for low-latency self-coherent optical communication systems [24]. We therefore envisage a coherent communication network that can be enhanced by large on-chip SBS gain.

The outstanding issues for SBS-based MWP are the high-power consumption due to the strong optical pump, a high noise figure attributed to the thermal phonons, and a limited number of compatible platforms that support SBS and functional components. Hence, it is expected that considerable efforts will be made in the near future to: 1) increase the SBS gain coefficients through careful engineering of the waveguides and materials, thus reducing the power requirements, 2) design systems that mitigate SBS noise and, 3) hybrid-integrate the SBS platform with optoelectronic components: laser, modulator, detector as well with passive components: couplers, gratings, mode-convertors to take SBS-based MWP out of the laboratory and into the commercial world.

6. References

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