

# Microwave Photonic Signal Processing Based on Stimulated Brillouin Scattering

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**Abstract**—In this report, stimulated Brillouin scattering (SBS) in optical single-mode fiber (SMF) was measured. Since the SBS can provide controllable phase shift near the Brillouin frequency shift, a microwave photonic Hilbert transformer can be achieved when the phase shift is set as  $\pi$ . A proof-of-concept experiment was constructed and a preliminary result of Hilbert-transformed Gaussian pulse was obtained.

**Index Terms**—stimulated Brillouin scattering, signal processing, Hilbert transformer, and microwave photonics

## I. INTRODUCTION

MICROWAVE photonics is an interdisciplinary which takes advantages of photonic systems, such as large bandwidth, wide tunability, low loss, light weight, and immunity to electromagnetic interference, to assist microwave systems achieving functions that are very complex or impossible to be carried out directly in the RF domain [1]. Photonic microwave signal processing has been drawing particular attentions especially in radars and communication systems. Among all the research topics in this area, stimulated Brillouin scattering (SBS)-based photonic microwave signal processing technologies have been rapidly developed due to its narrowband nature, reconfigurable capability and convenient to be integrated in optical networks [2]. Take multi-wavelength laser sources or optical frequency comb (OFC) as an example, it has attracted considerable interest in optical arbitrary waveform generation, fiber-optic sensing networks and photonic microwave signal processing. The stability, tunability, flatness and a fixed phase relationship between the comb lines are of great importance. A flat OFC based on cascaded SBS assisted by a stocks wave recycling loop has been experimentally demonstrated [3]. A more important microwave signal processing block is microwave photonic filter (MPF), which is commonly realized by finite impulse response (FIR) structure. However, the periodicity in these filter transfer functions is essentially limited their practical applications. Different from FIR filters, Brillouin gain spectrum can simply act as a microwave photonic filter without periodicity. The central frequency can be tuned simply by adjusting the pump wavelength and the profile of the filter is programmable by overlaid pump waves. In addition, a single

Brillouin gain peak can be treated as a tap like conventional filters so that multi-tap MWP filters can also be obtained based on dynamic Brillouin gratings (DBGs) in polarization maintaining fibers (PMFs) [4]. Quadrature filter, also known as Hilbert transformer is a basic processing block for microwave signal processing, which has a unity magnitude response and a  $\pi$ -shift at the center frequency. It can be implemented both electrically and optically. Different from all-optical Hilbert transformers, microwave photonic Hilbert transformers (MPHT) are used to process microwave signals in the optical domain. That means a microwave frequency response corresponding to a microwave Hilbert transformer in a microwave photonic system is needed to realize the MPHT. In this project, the SBS effect in optical fibers including both gain and loss was measured. It is found that SBS has a similar microwave response to Hilbert transformer, thus a MPHT based on SBS is proposed and a proof-of-concept experiment was carried out to get the preliminary results.

## II. STIMULATED BRILLOUIN SCATTERING

Stimulated Brillouin scattering is a bi-directional interaction between mechanical and electromagnetic waves, during which a frequency-shifted Stokes wave and an acoustic wave are generated. The scattered light is in all directions, but only backward (Stokes) and forward (anti-Stokes) light can exist in optical fibers. Assuming that the Stokes light is traveling in  $+z$  direction and the pump light is traveling in the  $-z$  direction, the amplitude of the Stokes light  $E_s(z, \omega)$  is given by [5]

$$E_s(z, \omega) = E_s(0, \omega) \exp(g I_p z) \quad (1)$$

Where

$$g = g_0 \frac{1}{1 + 2i(\omega - \omega_p + \Omega_B)/\Gamma_B} \quad (2)$$

is the complex SBS gain factor,  $\Gamma_B$  is the Brillouin linewidth,  $g_0$  is the line center gain factor,  $\omega_p$  is pump frequency and  $\Omega_B$  is the Brillouin frequency shift. Equation (2) is valid when  $\Omega_B \gg \Gamma_B$ .  $\Omega_B$  and  $\Gamma_B$  are intrinsic parameters of materials, for instance, silica fibers usually have a Brillouin frequency shift of around 11 GHz and a Brillouin linewidth of  $\sim 30$  MHz. The SBS effect including gain and loss in a 20-km single-mode fiber (SMF) was tested by an optical vector network analyzer [6] and shown in Figure 1. The measured Brillouin frequency shift ( $\Omega_B$ ) and linewidth ( $\Gamma_B$ ) is 10.6 GHz and 29.8 MHz, respectively. Phase shift is related to optical power [6], higher optical power can get larger phase shift, as shown in Figure 1.

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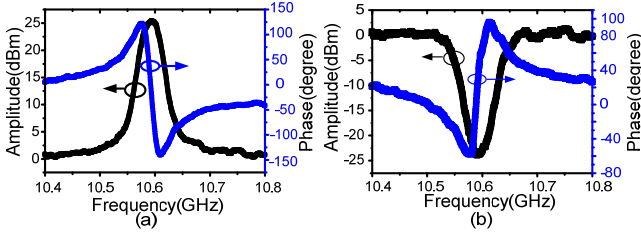


Figure 1. (a) SBS gain spectrum and phase response, and (b) SBS loss spectrum and phase response. Black and blue lines represent amplitude and phase responses, respectively.

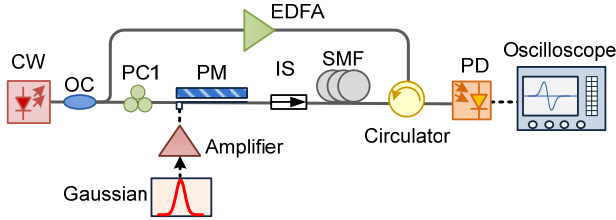


Figure 2. Schematic diagram of the proposed microwave photonic Hilbert transformer. OC: optical coupler; PC: polarization controller; OF: optical filter; IS: isolator; PM: phase modulator; SMF: single-mode fiber; PD: photodetector; EDFA: erbium-doped fiber amplifier. The grey full lines and black dotted lines represent optical and electrical link respectively.

### III. MICROWAVE PHOTONIC HILBERT TRANSFORMER

The frequency response of an MPHT can be expressed as

$$H_{HT}(\Omega) = \begin{cases} e^{-j\pi/2}, & \Omega < \Omega_0 \\ e^{j\pi/2}, & \Omega > \Omega_0 \end{cases} \quad (3)$$

where  $\Omega$  is the microwave angular frequency and  $\Omega_0$  is the microwave carrier frequency, or the center frequency of the Hilbert transformer. An ideal Hilbert transformer has a unity magnitude response over an infinite bandwidth and a  $\pi$ -shift at  $\Omega = \Omega_0$ . However, a practical Hilbert transformer must have a finite bandwidth. As can be seen in Figure 1, SBS has a controllable phase shift near the Brillouin frequency shift, which can be used to form a fractional Hilbert transformer. When the phase shift is set as  $\pi$ , a traditional MPHT is achieved. To demonstrate the SBS-based HT, a proof-of-concept experiment is carried out. The schematic diagram of the proposed experiment is shown in Figure 2. A continuous-wave (CW) optical carrier generated by a laser diode (LD) is split into two branches. In the lower branch, the optical carrier is coupled to a phase modulator (PM), to which a microwave signal to be Hilbert transformed is applied. Then, the optical signal at the output of PM is sent to a 20-km optical SMF. The upper branch of the optical carrier is amplified by an Erbium-doped fiber amplifier (EDFA) and applied to the SMF from the backward direction by an optical circulator to serve as the SBS pump signal. The output signal from the optical circulator is launched to a photodetector (PD), by which the Hilbert transformed signal is obtained. According to Section II, the SBS gain or loss are located at the Brillouin frequency shift, so in our experiment, the microwave signal to be Hilbert transformed is generated by a baseband Gaussian pulse signal mixed with a RF carrier at the Brillouin frequency shift. The baseband Gaussian pulse and RF carrier are generated by a pulse pattern generator (PPG, Anritsu MP1763C) and an analog signal source (Agilent E8257D),

respectively. A real-time oscilloscope is used to observe the waveforms. The original Gaussian pulse is shown as the solid line in Figure 3. After going through the proposed system, the waveform of the output signal is depicted as the dashed line in Fig. 3. As can be seen, the Hilbert transforming is realized based on SBS effect.

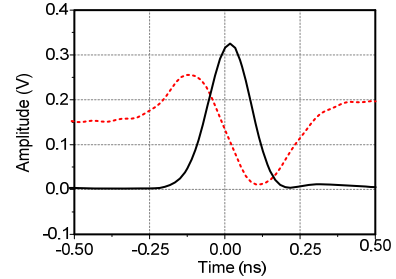


Figure 3. Waveforms of the original Gaussian pulse (Solid line) and the transformed pulse (dashed line).

### IV. CONCLUSION

In this project, stimulated Brillouin scattering in optical single-mode fibers was theoretically and experimentally investigated. Since the phase shift near Brillouin frequency shift is controllable by the optical power, a microwave photonic Hilbert transformer is proposed based on SBS. A proof-of-concept experiment was conducted and a Hilbert-transformed Gaussian pulse was achieved. Simply by adjusting the optical power, a fractional Hilbert transformer might be obtained.

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