

Multi-order millimeter-wave generation using stimulated Brillouin scattering and four-wave mixing

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This paper presents a hybrid all-optical approach for multi-order millimeter-wave (mm-wave) generation using the combined effects of stimulated Brillouin scattering (SBS) and four-wave mixing (FWM) in optical fibre. The proposed method employs a single-laser source which is used to induce SBS-generated Stokes and anti-Stokes components, which further participate in non-linear FWM processes inside the fibre. The cascaded interaction of these nonlinear phenomena produces multiple optical sidebands with precise frequency spacing. When detected by a high-speed photodiode, the beating between these multi-order components results in the generation of stable and high-purity mm-wave signals various frequency level at 11, 22, 33, 44, 55, and 66 GHz. The influence of pump power, fibre length, SBS gain, and nonlinear coefficient on the efficiency of higher-order frequency generation is analysed. Results show that combining SBS with FWM enhances spectral broadening, increases the number of generated sidebands, and enables the production of higher-order mm-wave signals with improved tunability. This multi-order optical mm-wave generation technique offers a low-power, flexible, simple structure and O–E–O free solution suitable for next-generation high-capacity communication systems, including 5G/6G and radio-over-fibre applications.

Keywords: millimeter wave generation, stimulated Brillouin scattering, stoke wave, four wave mixing.

1. Introduction

Millimeter-wave (mm-wave) generation has emerged as a critical research area driven by the rapid evolution of high-capacity wireless communication, radar sensing, fiber–wireless convergence, and upcoming 6G systems. The high bandwidth requirements of electronic devices limit the traditional electronic generation approach [1]. Using

photonic techniques such as frequency multiplication, optical heterodyning, optical nonlinearities, and the creation of optical frequency combs are the best alternative approach to this problem [2]. Compared to traditional electronics methods, photonic methods for producing millimeter-wave signals have a number of advantages, including reduced complexity, wide bandwidth, low phase noise, excellent stability, and wide frequency tunability [3,4]. The mm-wave generation using the baseband signal and local oscillator (LO) signal were then applied to a dual parallel Mach–Zehnder modulator (DPMZM) or a dual drive Mach–Zehnder modulator (DDMZM), respectively, and the low-frequency component and the LO signal were suppressed by varying the modulators' parameters [5,6]. All of the mentioned techniques employ double-sideband (DSB) modulation, which causes dispersion in a single-mode optical fibre to produce power fading. As a result, they are limited to short-range gearbox. Four wave mixing and frequency quadrupling can produce millimeter waves, as seen in [7]. There are reports on 60 GHz generation and transmission performance using frequency multiplication techniques [8]. Although it requires additional optical modulators and an RF input signal, the frequency multiplication technique can produce millimeter waves at the expense of a complex structure. Optical frequency comb (OFC) creation is another effective method for producing millimeter waves. Optical modulators powered by RF signals can be used to implement OFC generation [9]. Cascaded optical modulators are used to produce high frequency carriers [10]. However, in order to generate millimeter wave signals, this system requires optical filters to choose the desired comb lines.

Among various photonic approaches, stimulated Brillouin scattering in optical fibers has distinguished itself as a highly promising mechanism for generating stable, narrow-linewidth mm-wave signals due to its intrinsic acoustic resonance and precise frequency shift characteristics. Early studies established SBS as an efficient mechanism for frequency shifting, amplification, and slow-light effects, laying the foundation for its use in mm-wave generation [11]. Subsequent advances introduced SBS-based upconversion techniques that exploit the superposition between a modulated optical carrier and an SBS-amplified sideband, enabling flexible frequency generation without requiring high-frequency microwave synthesizers or complex optical components [12]. The SBS gain bandwidth independence of modulation further enhances system adaptability. Parallel research explored various optical modulation schemes for mm-wave generation. Dual-parallel Mach–Zehnder modulators demonstrated the ability to produce high-order optical sidebands while suppressing unwanted components, enabling fifth-order, twelve-tupled, and even twenty-four-tupled frequency multiplication [13]. However, these systems faced limitations in transmission distance due to power penalties and bit walk-off effects, restricting long-reach radio-over-fiber applications unless optimized modulation formats were employed. All-optical microwave oscillators based on SBS have further advanced the field by eliminating the need for microwave electrical components or opto-electrical conversion. Designs integrating semiconductor optical amplifiers (SOAs) for envelope detection and feedback enable the direct

generation of single-mode photonic microwave signals. These oscillators exhibit excellent phase-noise performance, with tuning ranges spanning several gigahertz by adjusting the SBS pump wavelength [14]. Recent demonstrations of Brillouin-assisted optoelectronic oscillators (OEOs) and self-oscillating optical frequency comb (OFC) generators highlight the potential of SBS to improve spectral purity and achieve dense comb spacing around the Brillouin shift. Beyond oscillators, SBS has been incorporated into advanced modulation architectures. Techniques involving dual-parallel polarization modulators (DP-PolMs) and cascaded modulators have demonstrated mm-wave generation at frequencies such as 60 GHz [15] and even 160 GHz, using low-frequency RF drive signals with significant sideband suppression ratio (SSSR) and optical sideband suppression ratio (OSSR). These methods reduce hardware requirements while enabling efficient frequency multiplication, making them suitable for high-frequency radio-over-fiber (RoF) systems. In addition to mm-wave generation, SBS has also been explored for high-accuracy photonic frequency measurement systems. By superimposing gain and loss spectra to reduce SBS bandwidth, researchers have achieved improved frequency resolution, enabling the estimation of multiple unknown input signals within a compact architecture. However, all of the mentioned methods demand a complex structure including baseband data, an external RF source, and optical modulators. As a result, a basic structure without optical filters and an external RF signal is required.

Collectively, the literature demonstrates that SBS-based photonic systems offer substantial advantages for mm-wave signal generation, including ultra-low phase noise, precise frequency control, compact configurations, and compatibility with fiber transmission. However, challenges remain in optimizing cascaded SBS processes, reducing system complexity, and improving integration for practical deployment in next-generation communication networks. These developments motivate continued research into high-quality, efficient mm-wave generation techniques leveraging the unique properties of SBS.

In this study, we provide a method for producing millimeter waves generation using the optical frequency multiplication concept based on SBS and the four wave mixing effect in a single mode fibre with a simplified construction with minimum pump power.

2. Principle of operation

2.1. Fundamentals of SBS-based mm-wave generation

Stimulated Brillouin Scattering is a third-order nonlinear optical process arising from the interaction between the optical pump wave and acoustic phonons in a medium. The pump wave generates a counter-propagating Stokes wave experiencing a frequency downshift equal to the Brillouin shift ($\approx 10\text{--}11$ GHz in standard single-mode fiber). When this Stokes shift is combined with heterodyning or cascaded SBS processes, frequency differences in the mm-wave range can be synthesized. Early demonstrations of SBS frequency shifting focused on microwave photonic filtering and optical amplification.

These foundational studies later enabled development in photonic mm-wave sources exploiting the Brillouin frequency offset.

2.2. Experimental setup

Figure 1 shows the proposed scheme's diagrammatic representation. An optical carrier with a power of 10 dBm is released by a continuous wave laser operating at a core frequency of 193.1 THz. A 20 km bidirectional fiber receives this high power optical transmission via an isolator. A single laser source can be used in this method as both a signal source and a pump. Stimulated Brillouin scattering is triggered in the fibre when the optical power exceed the Brillouin threshold. With a frequency shift of 11 GHz with respect to the optical carrier, the backscattered stoke wave (f_2) begins to propagate in the opposite direction of the optical pump wave (f_1) [16]. The back dispersed wave receives the pump signal energy, which causes the pump power to decline. A photodetector operates as a square-law device, generating a term at the frequency difference ($f_1 - f_2$). This enables high-purity, tunable, and wideband mm-wave generation. At the photodetector, the pump and stoke wave signals are heterodyned, producing an 11 GHz radio frequency signal. SBS has an ultra-narrow line width (typically < 30 MHz), making SBS-generated optical tones highly coherent. This results in mm-wave signals with very low phase noise, superior frequency stability, and better overall performance compared to electronic oscillators.

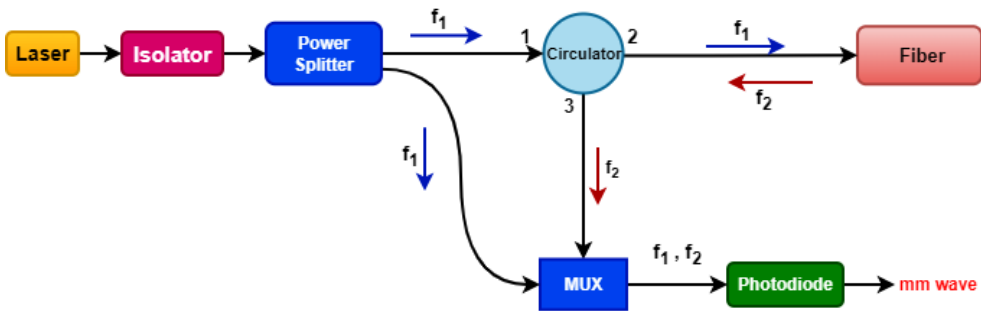


Fig. 1. Block diagram of 11 GHz mm wave generation system.

Two of the most effective optical nonlinearities are four-wave mixing and stimulated Brillouin scattering, which can provide multi-order frequency components appropriate for high-frequency mm-wave and sub-THz applications.

A hybrid multi-order generation technique is made possible by combining SBS with FWM, where the narrow-line width stokes signals from SBS act as stable seeds for effective FWM sideband expansion. The production of high-frequency mm-wave tones that might not be possible with SBS or FWM alone is supported by this hybrid integration, which also greatly increases spectral purity and conversion efficiency. When photo detected, the resulting optical lines result in mm-wave carriers with better tun-

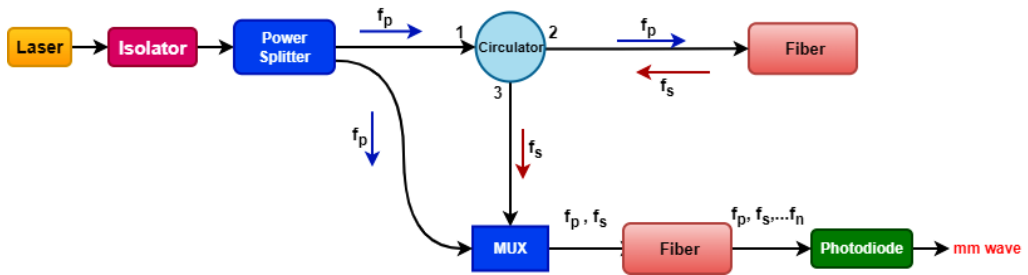


Fig. 2. Multi-order mm-wave generation using SBS and FWM effect.

ability, reduced noise, and broader frequency coverage, making them appropriate for high-capacity optical interconnects, radio-over-fiber (RoF), fiber-wireless systems, and detecting radars.

As per theory four wave mixing (FWM) occurs when the single mode fiber receives the pump (ω_p) and stoke wave (ω_s). Four-wave mixing generates two new degenerate frequency components, located at $(2\omega_p - \omega_s)$ and $(2\omega_s - \omega_p)$, which arise from the nonlinear interaction between the pump and stoke waves. The pump wave (ω_p) and the stoke wave (ω_s) that is generated by SBS in bidirectional fiber provide pump and probe signals to the four-wave mixing process in SMF. As per Fig. 2 in order to generate additional high-frequency carriers, output of back scattered signal is combined with laser source and sent to SMF. This SMF in term generates more comb lines and thereby can generate desired mm-waves at the Photo detector. This approach removes the requirement for an external RF source as well as additional optical modulator and optical filtering components. Therefore, we can suggest multi-order mm-waves generation via SBS and FWM alone, which are strong photonic techniques. This method combines the broadband potential of four-wave mixing with the stability of Brillouin scattering, and thus offer a flexible platform for next-generation wireless communication systems. The key simulation parameters and their corresponding values used in the proposed system are summarized in Table 1.

T a b l e 1. Simulation parameters.

Parameter	Value
Laser frequency	193.1 THz
Power of the laser source	10 dBm
Optimized fiber length	20 km
Responsivity of photodiode	0.8 A/W

3. Results and discussion

In this work, the proposed system is analyzed through multiple data-interpretation approaches to understand the influence of various physical parameters on the efficiency

of stimulated Brillouin scattering in fiber-based millimeter-wave generation. The performance evaluation primarily focuses on three key parameters: fiber length, input laser power, and effective core area of the fiber.

3.1. Effect of fiber length on SBS-generated millimeter-wave power

The corresponding optical and electrical output power are recorded when the fibre length is changed from 1 to 30 km. In Fig 3 the results are shown which demonstrate that the output mm-wave power grows continuously with fibre length up to roughly 20 km. This behaviour is related to the greater SBS gain gained during a longer engagement period. Typically, an increase in fibre length results in greater attenuation, which reduces the output power.

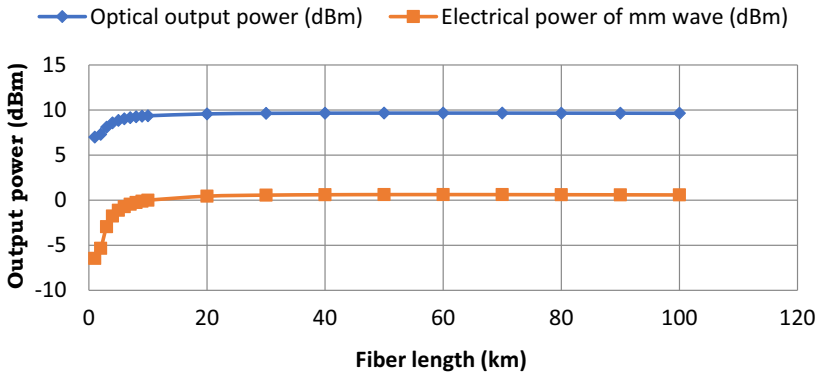


Fig. 3. Effect of fiber length on SBS-generated millimeter-wave power.

However, in SBS-dominant systems, the nonlinear Brillouin gain compensates for the fibre loss, leading to an overall net increase in signal power. The output power curve saturates after 20 km and does not significantly improve with additional length. When the Brillouin process reaches its gain limit and more fibre length merely adds to attenuation rather than gain, saturation results. Thus, 20 km is found to be the ideal fibre length for efficient SBS amplification in the suggested configuration, balancing nonlinear gain and transmission loss.

3.2. Effect of Input laser power on SBS gain and mm-wave output

The SBS response was also examined by adjusting the input pump power from 0 to 20 dBm. From Fig. 4, the obtained results indicate that the mm-wave output power increases dramatically with pump power up to roughly 16 dBm. An increase in pump intensity immediately increases the Stokes power in this area, where the SBS process is in its exponential gain phase. Beyond 16 dBm, the improvement in mm-wave output becomes marginal due to pump depletion, SBS gain saturation, and the onset of competing nonlinearities such as self-phase modulation (SPM) and four-wave mixing. To ensure

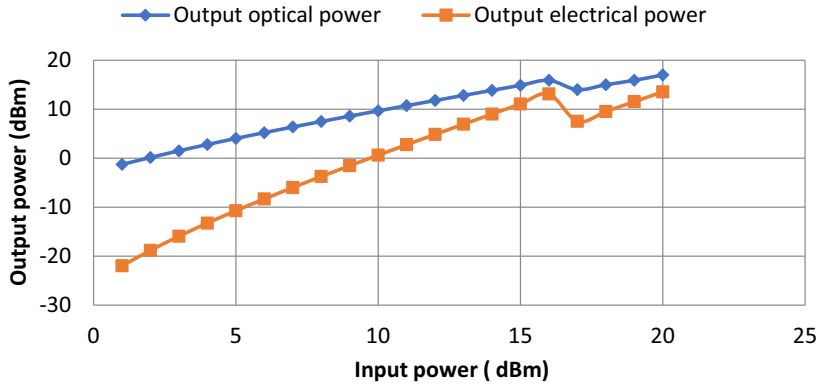


Fig. 4. Effect of input laser power on SBS gain and mm-wave output.

stable system operation without introducing excess nonlinear distortions, an optimized input laser power of 10 dBm is selected for the proposed design, offering a balance between strong SBS gain and system stability.

3.3. Influence of effective core area on SBS efficiency

The effective core area A_{eff} of the optical fiber has a direct influence on the SBS threshold power, given by the relationship:

$$P_{\text{th}} = \frac{A_{\text{eff}}}{g_{\text{B}} L_{\text{eff}}}$$

where g_{B} is the Brillouin gain coefficient and L_{eff} is the effective interaction length. Simulation results demonstrate that when the effective core area increases, the SBS threshold power likewise increases, consequently lowering the overall nonlinear efficiency. Consequently, the mm-wave output power drops for fibres with larger A_{eff} , as the pump power becomes insufficient to cause strong Brillouin scattering. This trend shows the need of selecting fibres with small effective core areas—such as highly nonlinear fibres (HNLFs) for better SBS-based mm-wave generation.

3.4. Single order and multi-order mm-wave generation

A 20-kilometer-long bidirectional fibre is used to launch a continuous wave laser with a power of 10 dBm at 1552.5 nm. This plan is put into practice in the Opti system evaluation tool. Stimulated Brillouin scattering was enabled when the high power pump wave passed over SMF [16]. Consequently, a stoke wave with a wavelength detuning of 0.1 nm and a frequency of 193.089 THz (11 GHz frequency shift) in relation to the carrier signal is produced, as illustrated in Fig. 5(a).

Next the combined pump wave (193.1 THz) and stoke wave (193.089 THz) interact within each other. The combined signals are applied to photo detector. It will pro-

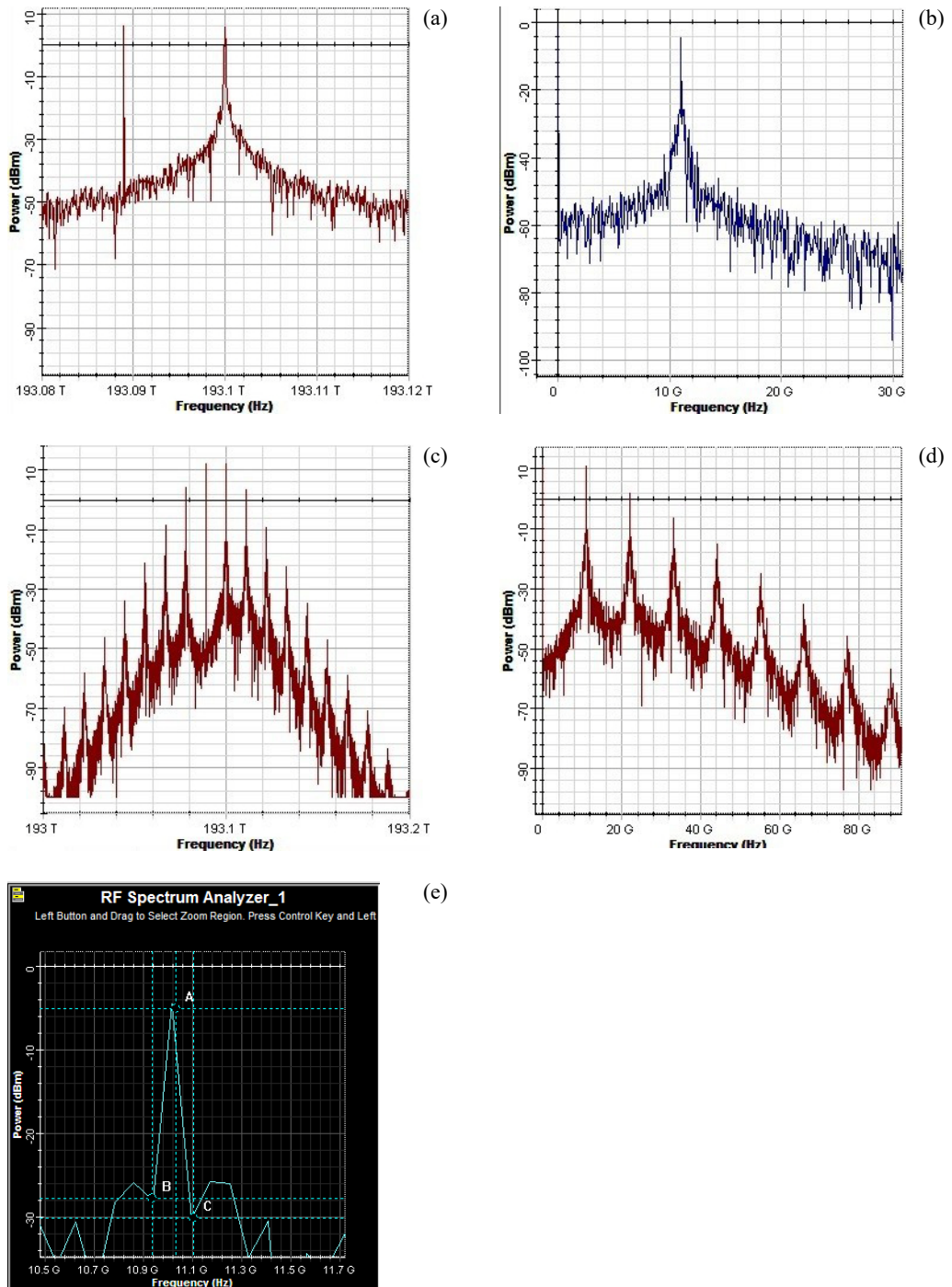


Fig. 5. (a) Optical spectrum. (b) RF spectrum. (c) Multi-order optical spectrum. (d) Multi-order RF spectrum. (e) Calculation of spectral purity.

duce the 11 GHz RF signal in the output. In this method we have not used any amplifier, modulator and any type of RF signal and devices. The advantage is the minimum pump power. SBS has the lowest nonlinear threshold (5–7 mW), enabling efficient mm-wave generation using low-power lasers.

SBS-based mm-wave generation is important due to its low phase noise, high stability, efficiency, tunability, and seamless integration with fiber-optic communication systems. It is a key enabling technology for future 6G and THz communication networks. SBS occurs within optical fiber, enabling simultaneous mm-wave generation and low-loss transport, which is perfect for the remote antenna units, distributed antenna systems and 5G/6G fronthaul applications. Due to four wave mixing, SMF generates two new frequency components (193.078 THz, blue shifted frequency, and 193.111 THz, red shifted frequency), which are displayed in Fig. 5(a), because the blue shifted frequency component is much attenuated compared to the red shifted frequency [14]. As shown in Fig. 5(d), millimeter waves (11, 22, 33, 44, 55, and 66 GHz) are detected at photo detector with significant powers level.

These sidebands are heterodyned, and the photo detector (PD) can produce more millimeter waves. The effect of the input power on the FWM efficiency is investigated. As per this experiment, when the pump power exceed 16 dBm, stokes power halted and hence there is no SBS process. This is then stopping the influenc of FWM in the typical fiber and production of mm-wave.

The spectral performance of the system is evaluated using sideband power suppression ratio (SPSR) and channel bandwidth for single-stage and multi-order millimeter-wave generation. From Fig. 5(e) the single-stage configuration achieves an SPSR of –22.7 dB with a bandwidth of 169 MHz. In multi-order generation, lower harmonic orders show better spectral purity, while SPSR degrades as the harmonic order increases. Conversely, the channel bandwidth increases with harmonic order, indicating a trade-off between spectral purity and bandwidth. The achieved spectral width is adequate for wireless communication applications and effectively avoids interference with nearby channels. Overall, the results suggest that lower harmonic orders are preferred for applications demanding great spectral purity, whereas larger harmonic orders are advantageous when wide bandwidth is prioritised. These results offer useful advice for choosing a suitable harmonic order based on system-level specifications. A conversion efficiency of about –9 dB is attained for the single-stage mm-wave generating technique. By reducing undesired sidebands and increasing nonlinear mixing efficiency, the application of SBS-assisted multi-order FWM greatly improves both characteristics.

4. Conclusion

This work combines four-wave mixing with stimulated Brillouin scattering to propose a straightforward and economical photonic technique for multi-order millimeter-wave generation. Without the use of external modulators, RF sources, optical amplifiers, or multiple lasers, the suggested approach uses SBS to produce the necessary frequency

-shifted optical tones, which then serve as input components for effective degenerate FWM. The technique effectively accomplishes frequency doubling and tripling using a single light source, proving the production of stable microwave and millimeter-wave signals at 11, 22, 33, 44, 55, and 66 GHz via optical heterodyning at the photodetector. The results show that the SBS Stokes power and fibre nonlinear properties have a significant impact on the strength and efficiency of the generated FWM components. The suggested hybrid technique allows for reliable and adjustable high-frequency signal production by combining the broadband mixing capacity of FWM with the narrow linewidth and high spectral purity of SBS. For the next-generation wireless communication systems, such as radio-over-fiber links, 5G/6G networks, and sub-THz applications, multi-order mm-wave generation employing SBS and FWM offers a potent and adaptable photonic solution.

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