Ultra-Low Linewidth Frequency Stabilized Integrated Lasers: A New Frontier in Integrated Photonics

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Abstract: With the advancement of photonic integration technology, ultra-low linewidth frequency-stabilized lasers have demonstrated significant potential in precision measurement, quantum communication, atomic clocks, etc. This review summarizes the latest developments in integrated photonics for achieving ultra-low linewidth lasers, particularly breakthroughs made by integrating Brillouin lasers. We discuss the design principles, manufacturing processes, performance characteristics, and potential value of these lasers in various applications.

Keywords: photonic integrated circuit (PIC); ultra-low linewidth; Brillouin lasers; high Q-factor

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1 Introduction

Photonic integrated circuits (PICs) offer a pathway to reduce costs, complexity, power consumption, and sizes by integrating various optical functions at the chip scale[1 – 4]. However, many high-end applications, such as quantum communication[5], atomic clocks[6], and precision measurement[7 – 9], require wavelengths and performance levels that current silicon-based photonic platforms struggle to achieve. To meet these demands, next-generation photonic integration requires ultra-broadband photonic circuit platforms spanning from ultraviolet to infrared[10 – 11]. These platforms should possess low loss, high power handling capabilities, and a rich array of linear and nonlinear circuit functionalities.

With the advent of the information age, the demand for precision measurement and high-speed communication continues to grow[12 – 14]. Ultra-low linewidth lasers have become increasingly important due to their advantages in frequency stability and coherence[12 – 19]. Traditional ultra-low linewidth laser systems, due to their size and cost, have been constrained in application across various fields. The development of integrated photonics offers the potential to create miniaturized, low-cost and, ultra-low linewidth lasers[20 – 21]. This article reviews the latest advancement in integrated photonics for achieving ultra-low linewidth lasers, with a particular focus on integrated Brillouin lasers that utilize phonons generated through light-matter interactions to achieve linewidth narrowing[22 – 24].

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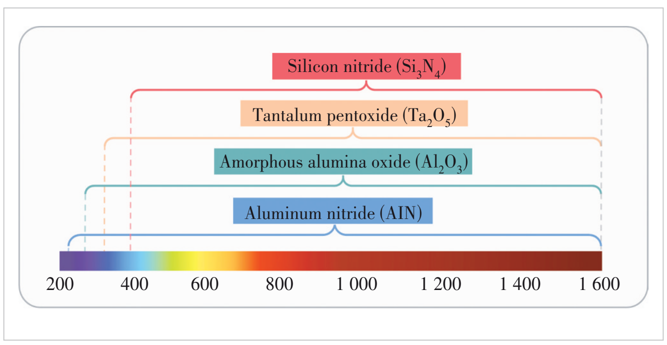
2 Development of Integrated Photonics

Integrated photonics has become a hotspot in engineering technology in recent years. By integrating active devices such as lasers, optical amplifiers, modulators, and photodetectors, along with various passive components on a single chip, integrated photonics enables complete optical systems. PICs have a wide range of applications, including high-speed optical communication[25], quantum communication[1, 26 – 27], biosensing[28 – 29], and precision measurement[6 – 9]. This technology provides effective means to reduce costs, simplify system complexity, and decrease power consumption and sizes.

Silicon-based photonic integration technology has garnered significant attention due to its compatibility with mature complementary metal-oxide-semiconductor (CMOS) processes[30 – 33]. This compatibility not only lowers manufacturing costs but also allows for the use of existing CMOS foundries and related manufacturing ecosystems[34]. The advantages of silicon-based photonic integration lie in the high refractive index contrast with oxide materials, enabling strong confinement of optical modes within waveguides[35]. Additionally, the silicon-on-insulator (SOI) waveguide structure exhibits extremely low propagation loss. Moreover, III-V active materials can be easily integrated with SOI technology to achieve heterogeneous integration, providing optical gain for photonic integrated circuits and further enhancing their complexity and performance[36–37].

However, silicon materials have certain limitations. The indirect bandgap of silicon (1.1 eV) results in higher waveguide loss and lower transparency at shorter wavelengths, such as visible and ultraviolet light[38]. Furthermore, silicon's power handling capacity is limited due to nonlinear losses, which restricts its performance in some high-end applications[39]. To overcome these limitations, researchers are exploring novel integrated photonic platforms based on wide bandgap semiconductor materials[40–42]. Materials such as silicon nitride (Si_3N_4)[43–44], aluminum oxide (Al_2O_3)[10, 45], aluminum nitride (AlN)[46–47], and tantalum pentoxide (Ta_2O_5)[48] have become focal points in integrated photonics research due to their excellent optical transparency, low-loss characteristics, and outstanding mechanical and chemical stability. Fig. 1 illustrates the application space of different wavelength windows ranging from ultraviolet (200 nm) to infrared (2 350 nm).



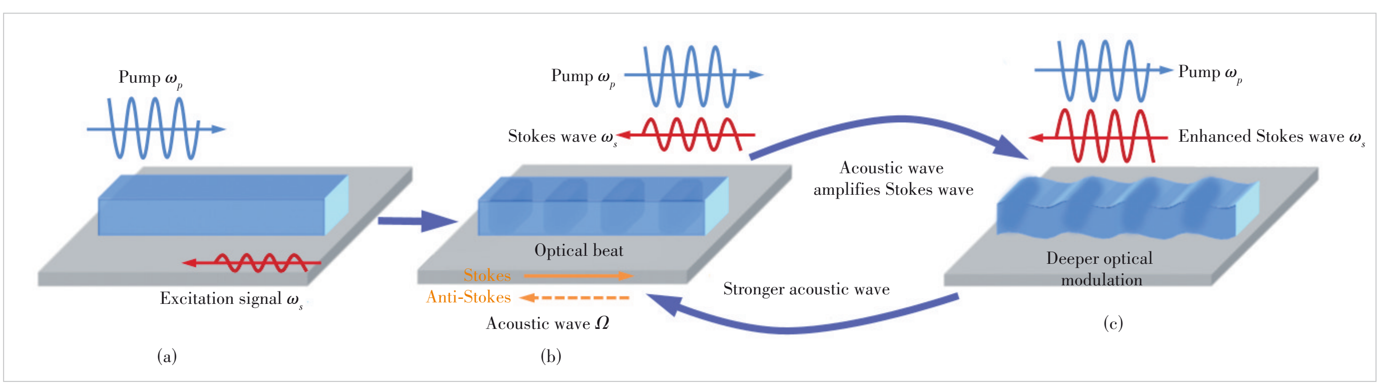
▲**Figure 1. Next generation optical waveguide platforms and wavelength transparency based on the bandgap (Si_3N_4, Ta_2O_5, Al_2O_3, and AlN)[49]**

Si_3N_4 is particularly noteworthy due to its extremely low transmission loss in the visible to infrared wavelength range. Coupled with its high refractive index contrast, Si_3N_4 provides an ideal platform for realizing compact photonic devices with high-performance[50–51]. Al_2O_3 stands out for its low-loss characteristics and high refractive index in the ultraviolet to visible wavelength range, making it a key candidate material for high-precision optical sensors and spectrometers[10]. Meanwhile, AlN offers transparency in the ultraviolet range and a high electro-optic coefficient, indicating its potential applications in high-speed electro-optic modulators and ultraviolet photonics[52].

Future research will focus on further reducing waveguide losses, improving Q-factors, achieving a broader wavelength tuning range, and enhancing the environmental stability of lasers. Additionally, the development of new materials, innovations in manufacturing processes, and the exploration of nonlinear optical effects will further propel the advancement of integrated photonics technology. With continuous technological breakthroughs and expanding applications, integrated photonics is set to play an increasingly crucial role in future scientific exploration and commercial applications.

3 Principles and Applications of Brillouin Lasers

Brillouin lasers represent a class of advanced lasers that achieve linewidth narrowing through the interaction of light with phonons generated via light-matter interactions. These lasers produce highly coherent and spectrally pure laser output by leveraging the nonlinear interactions between photons and phonons, demonstrating significant potential and value in applications ranging from the visible to the infrared wavelength range[24, 53–55]. Fig. 2 illustrates the principle diagram of Brillouin lasers, showcasing the interaction between optical and acoustic modes, which forms the basis of stimulated Brillouin scattering (SBS). In the case of backward stimulated Brillouin scattering (BSBS), a pump signal with a frequency of ω_p interacts with a counter-propagating signal of frequency ω_s, which can either be an excited signal or a pump scattering signal



▲**Figure 2. Stimulated Brillouin scattering: (a) an optical pump interacts in the medium with a counterpropagating seed at the Brillouin frequency shift; (b) when the optical beat generated by said tones matches the Brillouin frequency shift, electrostriction induces an acoustic wave; (c) a stronger Stokes wave is created. The proposed deeper optical modulation generates a stronger grating[58]** generated by thermal phonons. This interaction creates an optical beat pattern. When $\omega_p - \omega_s = \Omega$, the beat pattern enhances the acoustic wave through electrostriction. This enhanced acoustic signal, in turn, amplifies the Stokes wave via the photoelastic effect, creating a traveling refractive index grating. The pump light is strongly reflected by this refractive index grating, and due to the Doppler shift, the reflected wave precisely matches the Stokes frequency. The amplified Stokes signal further strengthens the acoustic mode, leading to a stimulated cycle where Stokes/anti-Stokes signals are further amplified[56].

3.1 Brillouin Laser Principles

The phenomenon of Brillouin scattering is central to the working mechanism of Brillouin lasers. It describes the interaction between photons and phonons as light propagates through a medium, resulting in a slight change in light frequency[57–59]. The specific principles are illustrated in Fig. 3, where SBS is identified as an inelastic scattering process. During this process, energy and momentum must be conserved. It can be categorized into Stokes (redshift) or anti-Stokes (blueshift) processes. The Stokes process generates phonons, lowering the energy of the photons, while the anti-Stokes process absorbs phonons, increasing the energy of the photons. SBS primarily involves two possible interaction processes based on the propagation directions of the pump and Stokes light: BSBS and forward stimulated Brillouin scattering (FSBS).

In Brillouin lasers, this interaction is utilized to narrow the laser linewidth. Depending on the implementation, Brillouin lasers are mainly divided into two categories: fiber-based[60–63] and waveguide-based[64–66]. Waveguide-based Brillouin lasers leverage the confined optical modes within waveguides to interact with phonons, producing laser output with high coherence. These lasers can achieve sub-hertz linewidths, providing new technological pathways for applications in precision measurement, quantum communication, and atomic clocks[56].

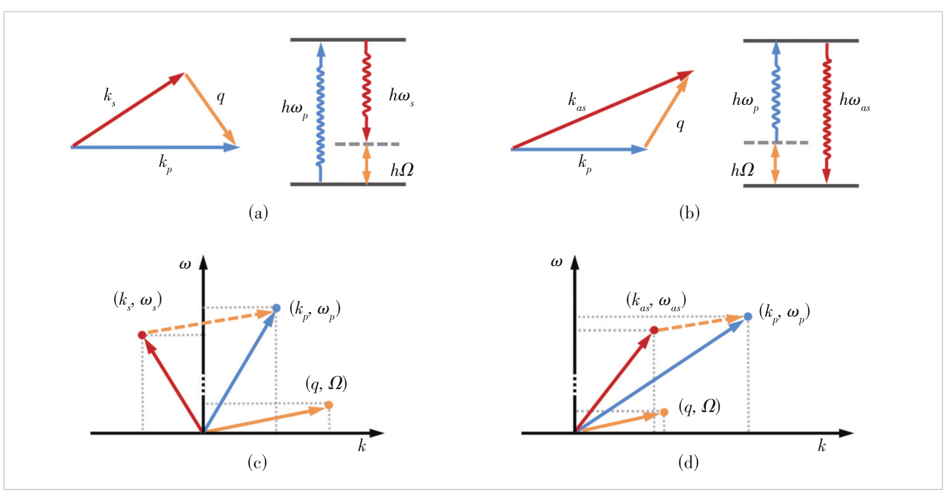
3.2 Technical Advantages and Applications

The unique advantage of Brillouin lasers lies in their ability to significantly narrow the linewidth of the pump laser through nonlinear phonon interactions, resulting in laser output characterized by low white noise, low close-to-carrier frequency noise, and low relative intensity noise (RIN)[67–69]. These features make Brillouin lasers indispensable in fields that require extremely narrow linewidth and high stability, such as precision measurement and quantum communication. Additionally, the ultra-narrow linewidth of Brillouin lasers shows great potential for applications in optical frequency standards, microwave photonics, and optical atomic clocks[67–72].

With the advancement in materials science and micro-nano fabrication technologies, the integration and performance of Brillouin lasers are expected to improve further. Future research will focus on enhancing the frequency stability of these lasers, reducing system costs, and exploring new integration platforms and materials to enable broader applications[56]. In particular, using wide bandgap semiconductor materials, such as Si_3N_4, Al_2O_3, and AlN, will offer new possibilities for extending Brillouin lasers' operation from the ultraviolet to the infrared wavelength range.

4 Design and Fabrication of Integrated Brillouin Lasers

The design and fabrication of integrated Brillouin lasers is a complex process requiring a balance among several critical parameters. The primary objective is to achieve a high Q-factor for narrow linewidth laser output while maintaining low waveguide loss to ensure high efficiency of the laser[71–76]. During the design process, the interaction between the pump light and Stokes light must be carefully considered. This interaction is achieved through precise waveguide structure design to enable efficient energy conversion and phase matching.



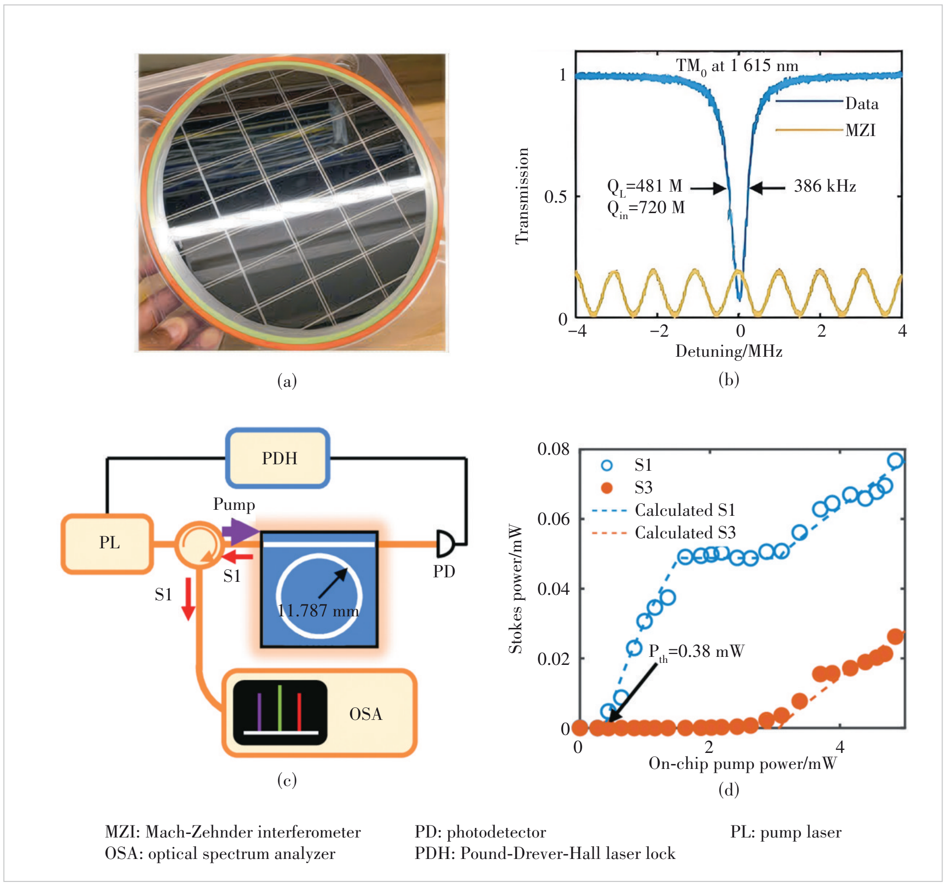
▲Figure 3. (a) Stokes process generates phonons, (b) anti-Stokes process absorbs phonons, (c) schematic of phase matching conditions for BSBS, and (d) schematic of phase matching conditions for FSBS

Waveguide loss is a crucial factor in the design as it directly impacts the performance and threshold of the laser. Losses arise not only from the inherent absorption of the material but also from the geometric structure of the waveguide, sidewall roughness, and surface scattering[72, 77]. To minimize these losses, designers employ various techniques including optimizing the cross-sectional shape of the waveguide, using low-roughness sidewalls and applying special coatings to reduce scattering.

The mode volume and Q-factor are two other key parameters influencing the performance of the laser. A high Q-factor resonator can enhance the intracavity optical field, thereby reducing the laser linewidth. Optimizing the mode volume helps achieve efficient pump and signal collection, which is critical for high-power laser output[78]. Fig. 4 shows a resonator with an intrinsic Q-factor as high as 720 million at a wavelength of 1 615 nm. The intrinsic linewidth of the resonator is 258 kHz, with a waveguide loss of 0.034 dB/m, and it is used to achieve a Brillouin laser with a threshold power of 380 μW. This study achieves high performance by combining a single-mode TM waveguide design with blanket etching and low-pressure chemical vapor deposition (LPCVD) of an 80 nm Si_3N_4 waveguide core. This core is integrated with a thermally grown under oxide cladding and a tetraethyl orthosilicate plasma-enhanced chemical vapor deposition (TEOS-PECVD) upper oxide cladding to reduce scattering losses[74].

The loaded and intrinsic Q-values are measured using a laser that tunes from 1 550 nm to 1 630 nm (Velocity TLB-6700), with a measured maximum of 720 million at 1 615 nm, corresponding to a propagation loss of 0.034 dB/m. An intrinsic linewidth of 258 kHz and a loaded linewidth of 386 kHz are measured using Mach-Zehnder interferometer (MZI) and ringdown techniques. They demonstrate a 380 μW threshold for the first order Stokes (S1) Brillouin lasing operating at 1 570 nm. A tunable laser is locked to the resonator using the Pound-Drever-Hall technique. Measurement of S1 on an optical spectrum analyzer (OSA) as a function of input pump power at 1 570 nm, shown in Fig. 4d, indicates a clear S1 threshold and a threshold power of 380 μW. Using the cascaded Brillouin laser model, we can simulate the S1 and S3 Stokes power shown as dashed curves in Fig. 4c, with the measured loaded and intrinsic Q at 1 570 nm and an estimated Brillouin gain of 0.043 mW^{-1}.

Material selection is crucial for the performance of integrated Brillouin lasers. Si_3N_4 is preferred due to its excellent optical and mechanical properties and low loss across a wide wavelength range[54, 74]. However, to cover a broader wavelength range or achieve specific functionalities, researchers are also exploring other materials such as lithium niobate on insulator (LNOI)[79], arsenic trisulfide (As_2S_3)[80–82], arsenic selenide (As_2Se_3)[83], and tantalum pentoxide (Ta_2O_5). These materials possess varying optical characteristics and mechanical properties, making them suitable for different application scenarios.



▲Figure 4. (a) A 200 mm wafer after the manufacturing and dicing process; (b) resonance spectrum scan at 1 615 nm using a 1.078 MHz FSR Mach-Zehnder interferometer; (c) setup for the SBS laser; (d) measured on-chip power for S1 and S3 with the calculated curves, indicating a threshold of 0.38 mW[74]

The fabrication of waveguides typically begins with the deposition of a Si_3N_4 thin film on a silicon substrate, a process that can be accomplished using LPCVD or PECVD techniques[51, 84]. After deposition, waveguide structures are formed through photolithography and etching processes. Precise control of the etching process is required to ensure the accuracy of the waveguide dimensions and the smoothness of the sidewalls, thereby reducing scattering loss.

After the waveguide structure is formed, a cladding layer is usually deposited to further reduce waveguide loss and protect the waveguide from environmental effects. The annealing step is crucial for eliminating internal stresses in the material and improving its optical quality, especially for Si_3N_4, where appropriate thermal treatment can significantly enhance its optical properties.

Heterogeneous integration techniques allow different material components to be integrated onto a single chip, facilitating the creation of more complex photonic circuits. For instance, integrating Si_3N_4 waveguides with III-V semiconductor lasers or detectors can construct complete photonic systems with signal amplification and detection functionalities[43].

Lastly, packaging technology is vital for protecting the laser from external environmental influences, ensuring long-term stability and reliability. The packaging process must consider optical coupling efficiency, thermal management, and compatibility with external fiber or electronic systems.

In summary, the design and fabrication of integrated Brillouin lasers require careful consideration of the waveguide loss, mode volume, Q-factor, material selection, and packaging. Advanced fabrication techniques and material choices are essential for optimizing laser performance and expanding its application potential.

5 Performance Optimization and Testing Methods

Optimizing the performance of integrated Brillouin lasers involves reducing the waveguide loss, increasing the Q-factor, and optimizing the linewidth. These parameters directly impact the laser's coherence, stability, and overall performance. Researchers employ various strategies and testing methods to achieve these optimization goals.

5.1 Reducing Waveguide Loss

The waveguide loss is a critical factor limiting laser efficiency. By optimizing the geometric structure of the waveguide, reducing sidewall roughness, and using low-loss materials, significant reductions in loss can be achieved. For instance, using Si_3N_4 materials and precise chemical vapor deposition (CVD) techniques can achieve loss levels as low as sub-decibel per meter.

5.2 Increasing Q-Factor

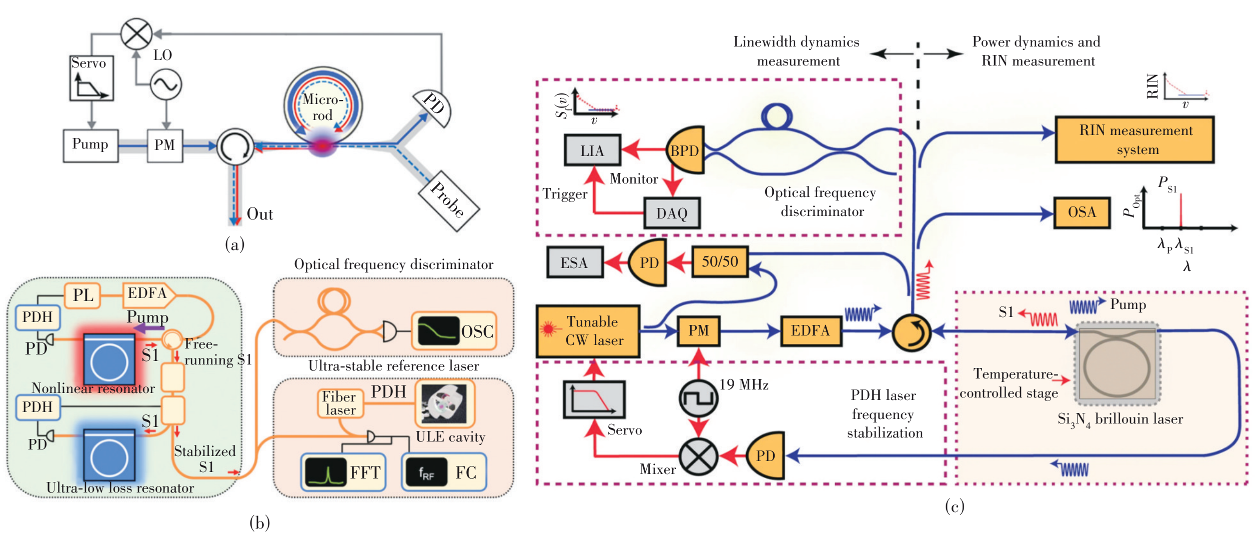
The Q-factor is an indicator of the resonator's quality and directly affects the laser's linewidth. Designing high-Q resonator structures and using high-quality materials can improve the laser's Q-factor[56]. For example, by precisely controlling the size and shape of the waveguide, Q-factors up to tens of millions can be achieved[72, 85].

5.3 Optimizing Linewidth

The linewidth of the laser is a critical indicator of its coherence. By precisely controlling the interaction between the pump light and Stokes light, sub-hertz linewidths can be achieved. Additionally, high-precision measurement equipment like radio-frequency-calibrated MZI can be used to accurately measure and optimize the laser's linewidth[86–88].

5.4 Testing Methods

Various testing methods are employed to evaluate laser performance[87–89]. High-precision optical spectrum analyzers are used to measure the laser's linewidth, while radio-frequency-calibrated MZIs are used to measure frequency noise[80, 86]. These testing methods not only evaluate the laser's performance but also guide further optimization efforts. Fig. 5 shows the measurement system for various parameters of the Brillouin laser.



AOM: acousto-optic modulator
BPD: balanced photodetector
CW: continuous wave
DAQ: data acquisition controller
EDFA: erbium-doped fiber amplifier
EOM: electro-optic modulator
ESA: electrical spectrum analyzer
FC: frequency counter
FFT: fast Fourier transform
LIA: lock-in amplifier
OSA: optical spectrum analyzer
OSC: oscilloscope
PD: photodetector
PDH: Pound-Drever-Hall
PL: pump laser
PM: phase modulator
Si_3N_4: silicon nitride
RIN: relative intensity noise

▲Figure 5. (a) Measurement setup of Brillouin laser loaded Q[68]; (b) Brillouin laser stabilization and frequency noise measurement[90]; (c) measurement setup of Brillouin laser linewidth, phase noise, relative intensity noise (RIN) and power dynamics[71]

6 Application Examples of Integrated Brillouin Lasers

Integrated Brillouin lasers, with their superior performance, demonstrate tremendous potential in various fields including atomic clocks, coherent communication, quantum communication, precision measurement, and spectroscopy.

6.1 Atomic Clocks

In atomic clocks, ultra-narrow linewidth lasers are crucial for achieving high precision in time measurement[6]. By locking the laser frequency to atomic transitions, extremely high-frequency stability can be attained. For instance, using an integrated Brillouin laser as the frequency source in atomic clocks can provide unprecedented time measurement accuracy.

6.2 Coherent Communication

In coherent communication systems, SBS lasers offer significant advantages. Firstly, due to their ultra-narrow linewidth and high coherence, SBS lasers can substantially reduce phase noise, thereby enhancing the quality and reach of signal transmission. This characteristic is particularly crucial in coherent optical communication systems, as phase noise directly impacts the accuracy of demodulating the modulated signal. Additionally, the low RIN of SBS lasers further improves the system's signal-to-noise ratio, ensuring data integrity and reliability in long-distance fiber optic communications[71].

Moreover, the high-frequency stability and low noise characteristics of SBS lasers make local oscillators and signal sources in coherent communication systems ideal. Precise control of the output frequency and phase of SBS lasers enables efficient wavelength division multiplexing (WDM) and dense wavelength division multiplexing (DWDM), significantly increasing the bandwidth and capacity of communication systems.

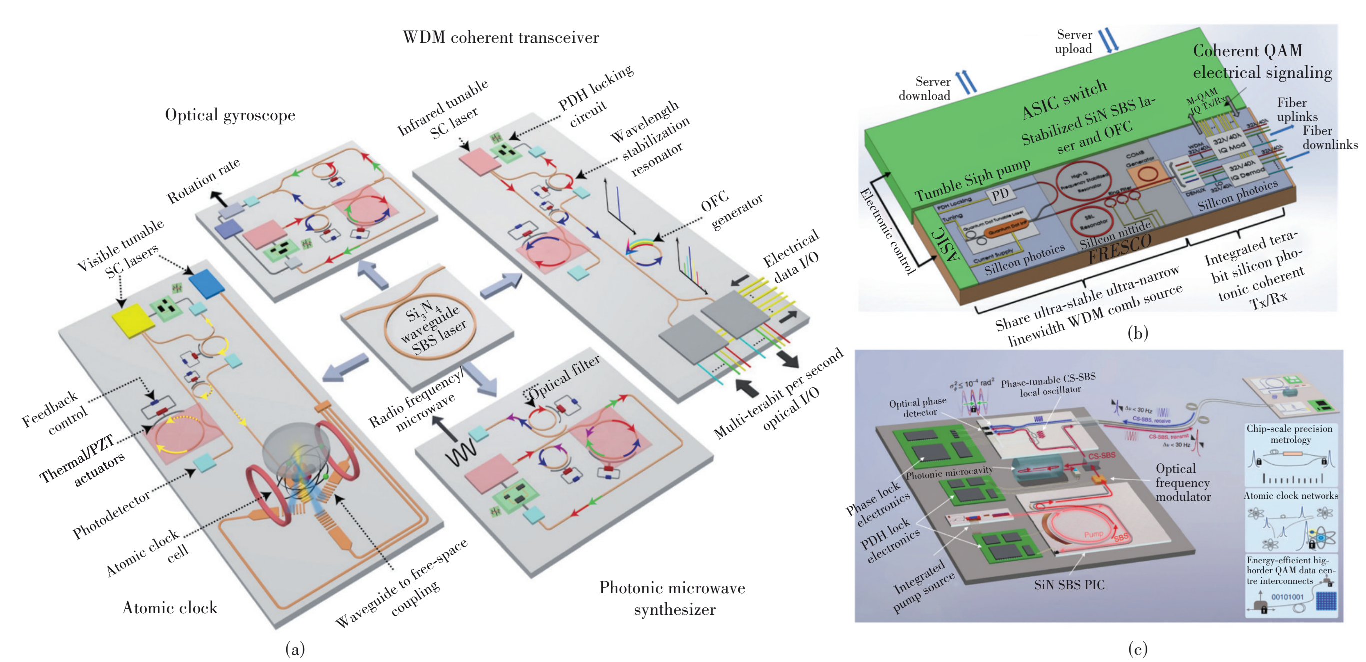
SBS lasers also possess flexible tuning capabilities, providing unique advantages in dynamic spectrum allocation and agile optical networks. Studies have shown that the SBS effect can achieve rapid and precise laser wavelength tuning, meeting diverse communication needs.

6.3 Quantum Communication

In quantum communication, integrated Brillouin lasers can generate entangled photon pairs, supporting quantum key distribution (QKD) and quantum computing. Their high coherence and stability make them ideal for implementing quantum communication networks[91–92].

6.4 Precision Measurement and Spectroscopy

The high coherence and low linewidth characteristics of integrated Brillouin lasers are invaluable in precision measurement and spectroscopy. They enable high-resolution spectroscopy, allowing for precise detection of molecular structures and chemical reactions. Fig. 6 illustrates some application examples of SBS lasers.

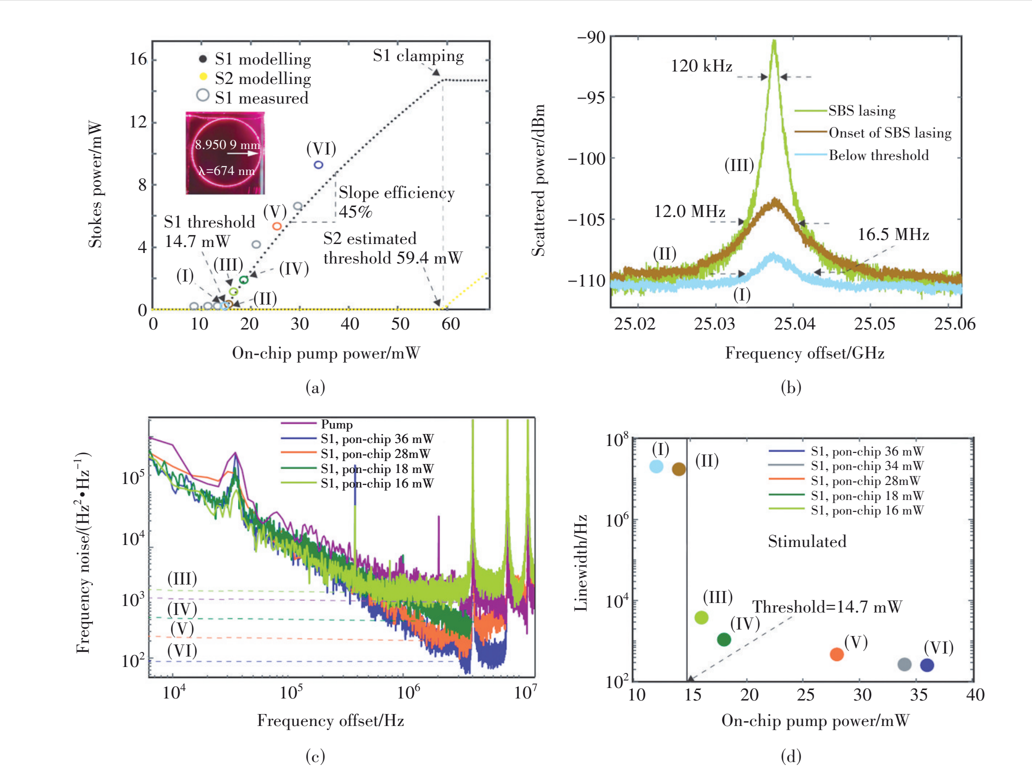


ASIC: application-specific integrated circuit
CS: carrier suppressed
OFC: optical fiber communication
PDH: Pound-Drever-Hall
PIC: Photonic integrated circuit
PZT: Lead Zirconate Titanate
QAM: quadrature amplitude modulation
SBS: stimulated Brillouin scattering
Si_3N_4: silicon nitride
WDM: Wavelength Division Multiplexing

▲Figure 6. Applications of SBS laser: (a) chip-scale atomic clock, integrated laser optical gyroscope, WDM coherent transceiver, and low-noise, photonic microwave synthesizer[71], (b) example applications in coherent optical communication[93] and (c) optically synchronized precision fibre link[94]

6.5 Experimental Validation

Researchers have experimentally validated the performance of integrated Brillouin lasers. For instance, an integrated Brillouin laser utilizing silicon nitride waveguides achieved a remarkable linewidth of 269 Hz at a wavelength of 674 nm, showcasing excellent coherence, as illustrated in Fig. 7[95]. Just above threshold (III), we see a dramatic 100× narrowing of the linewidth to 120 kHz as SBS dominates the emission. At all points above the threshold, we measure the frequency noise of S1 using an optical frequency discriminator (OFD). The fundamental linewidth (4 ν) is defined as the far-from-carrier white frequency noise floor in Hz^2/Hz, multiplied by π. In Fig. 7c, the noise floor for each pump power input is indicated by horizontal dashed lines (III-VI). As the pump power increases beyond the S1 threshold, the fundamental linewidth drops dramatically from 1.1 kHz (IV) to 269.7 Hz (VI). These linewidth results are summarized in Fig. 4d, indicating the integral linewidths for points (I-II) below the threshold and the fundamental linewidths for the frequency noise curves in (III-VI) in Fig. 4c. We cannot provide the required on-chip pump power, 59.4 mW, to achieve the lasing of the second order Stokes (S2). Future work will look further into noise properties measured using stabilized pump sources and exploring linewidth behavior as S1 approaches the S2 lasing threshold. Additionally, SBS laser demonstrations at a wavelength of 698 nm showcase the versatility of this laser design, suitable for probing neutral strontium atomic clock transitions.



SBS: stimulated Brillouin scattering

▲**Figure 7. Measurements of the Stokes threshold, power, and linewidth of the 674 nm SBS laser[95]**

7 Technical Challenges and Future Directions

Achieving ultra-narrow linewidth laser output with integrated Brillouin lasers has seen significant progress, yet several technical challenges remain. Key issues include reducing waveguide loss, increasing the Q-factor, achieving a broader wavelength tuning range, and enhancing stability against environmental changes. Reducing waveguide loss is critical for improving laser efficiency and linewidth. Future research will focus on new material combinations and waveguide designs to minimize scattering and absorption losses, such as through improved CVD techniques that control material composition and structure at the atomic level. Enhancing the Q-factor is essential for achieving narrow linewidth and high-frequency stability. Researchers will optimize the geometric parameters of resonators and use materials with high refractive index contrast. The development of advanced photonic crystals and metamaterials may also provide new opportunities for achieving higher Q-factor resonators.

7.1 Expanding the Wavelength Tuning Range

To enable integrated Brillouin lasers to cover a broader wavelength range from ultraviolet to infrared, researchers need to develop new material systems and design strategies. This may include employing multi-material heterogeneous integration techniques and developing novel wavelength-selective elements, such as gratings and filters.

7.2 Enhancing Environmental Stability

The environmental stability of integrated Brillouin lasers is crucial for their reliability in practical applications[95–97]. Future research will focus on developing effective thermal management and mechanical support structures, as well as exploring materials that are insensitive to changes in temperature, pressure, and chemical environments.

7.3 Exploring New Effects and Amplification Techniques

To further enhance laser

performance, future research will explore new nonlinear optical effects, such as four-wave mixing (FWM) and second-harmonic generation (SHG). These effects can be used to achieve broader wavelength tuning and more complex signal processing functions[21]. Additionally, developing more efficient pumping and signal amplification techniques will be key to improving laser performance.

7.4 Expanding Integrated Photonics Platforms

The expansion of integrated photonics platforms will support a wider range of applications, including quantum information processing, precision measurement, and atomic clocks. This will require further development of materials and devices to enable full-spectrum operation from ultraviolet to infrared, ensuring compatibility with existing technologies[70].

8 Summary

Integrated Brillouin lasers, as a significant branch of integrated photonics, have made remarkable progress in achieving ultra-narrow linewidth lasers. With their compact size, low cost, and high stability, these lasers are poised to play a crucial role in future scientific and commercial applications. As technology continues to advance, we anticipate that integrated Brillouin lasers will find applications and innovations in an expanding array of fields.

The development of ultra-narrow linewidth and frequency-stabilized integrated lasers offers new opportunities for precision science and commercial applications. The application of integrated photonics technology makes it possible to create compact, low-cost, and highly reliable laser systems. These systems have significant potential in high-end applications such as atomic clocks, quantum communication, and precision measurement. The high coherence and low noise characteristics of integrated Brillouin lasers provide new tools for precision measurement and are crucial for building quantum communication networks.

Despite the significant progress made in integrated Brillouin laser technology, a lot of challenges persist, and there is ample room for further enhancement. Future research will focus on further reducing waveguide loss, increasing the Q-factor, achieving a broader wavelength tuning range, and enhancing the environmental stability of the lasers. Additionally, the development of new materials, innovations in manufacturing processes, and exploration of nonlinear optical effects will further enhance the performance of integrated Brillouin lasers.

The development of integrated Brillouin lasers requires support from traditional disciplines such as physics, materials science, and optical engineering, and will benefit from interdisciplinary integration and innovation. For instance, advancements in quantum information science will provide new application scenarios for integrated Brillouin lasers, while developments in micro-nano fabrication technology will enhance the integration and performance of these lasers.

As technology matures and costs decrease, integrated Brillouin lasers are expected to gain wider adoption in the commercial market. From precision instrument manufacturing to communication network construction, and from fundamental scientific research to industrial process control, these lasers will play an important role. Over the coming years, integrated Brillouin lasers are expected to drive technological advancement and industrial upgrades in multiple fields.

The future of integrated Brillouin lasers is promising, and their importance in integrated photonics continues to rise. With ongoing technological breakthroughs and expanding applications, integrated Brillouin lasers are set to play an increasingly critical role, opening new avenues for scientific exploration and commercial applications.

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