The Versatile Applications of Distributed Bragg Reflector (DBR) Lasers: Sensing, Communication, And Beyond

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Abstract. Distributed Bragg Reflector (DBR) lasers have emerged as versatile and indispensable tools across various domains. Their advantages, including high signal-to-noise ratios, narrow linewidths, and support for distributed sensing, enable them to excel in diverse applications. DBR lasers have revolutionized optical fiber communication, medical diagnostics, and chaos-based key distribution. They provide precise control over wavelengths, making them valuable in fields such as dermatology, ophthalmology, and photodynamic therapy. Additionally, they play a critical role in flow cytometry, spectroscopy, and dental procedures. In the realm of sensing, DBR lasers have proven their efficacy in detecting parameters like temperature, pressure, current, magnetic fields, and ultrasound. Innovative techniques, such as FPGA-based demodulation and slotted DBR optical fiber lasers, have further enhanced their capabilities. As technology advances, the potential of DBR lasers in sensing and detection applications continues to grow. Their ability to deliver real-time, accurate data across various parameters positions them as essential tools for addressing complex scientific, medical, and industrial challenges. The future promises exciting developments in DBR laser technology, further expanding their role in solving multifaceted problems.

Keywords: DBR Lasers; Sensing Technology; Optical Fiber Communication; Medical Applications.

1. Introduction

Distributed Bragg Reflector (DBR) semiconductor lasers are widely applied in fields such as medical diagnostics, optical fiber communication, and laser sensing due to their exceptional wavelength stability and consistently high-power output characteristics. Given these attributes, this paper conducts an analysis, summary, and review of the characteristics, structure, and applications of DBR lasers [1]. Building upon this foundation, we summarize their development trends and discuss their future prospects.

This paper aims to explore the working principles of a novel optical device and its potential application scenarios. To begin with, a detailed analysis of its internal structure will be provided to gain a deeper understanding of the device's operational mechanism. Subsequently, the paper will place emphasis on its wavelength-tuning capabilities and resistance to thermal sensitivity, facilitating a better comprehension of its suitability under various environmental conditions. In the following sections, the paper will delve into the potential application scenarios of this device in multiple domains, including optical fiber communication, medical applications, and laser sensing, to showcase its broad spectrum of applications. Finally, through a comprehensive review of the research, conclusions will be drawn, and the development trends of this optical device will be discussed for future prospects.

2. Analysis of Working Principles

2.1. Internal Structure

A laser consists of three main components: a pump source, a gain medium, and a resonant cavity. The pump source excites the gain medium, leading to the emission of photons. The primary function of the resonant cavity is to amplify the laser radiation and compensate for optical power losses. The working principle of a semiconductor laser relies on the excitation process, utilizing semiconductor material (i.e., electrons) to undergo transitions between energy bands, resulting in photon emission

[2]. Two parallel reflecting mirror surfaces are formed on opposite sides of the semiconductor crystal, acting as mirrors for the resonant cavity, thereby enabling optical oscillation, feedback, and radiation amplification, ultimately leading to laser output.

Similar to traditional solid-state lasers, a Distributed Bragg Reflector (DBR) single-frequency fiber laser consists of a rare-earth-doped optical fiber serving as the gain medium. Wide-band fiber Bragg gratings (WB-FBG) and narrow-band fiber Bragg gratings (NB-FBG) are fused at both ends of the gain fiber and function as the front and rear cavity mirrors, forming the resonant cavity [3]. This configuration is illustrated in the figure 1 below.

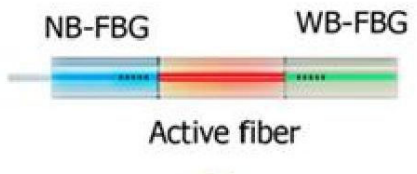


Fig. 1 Internal Structure of laser [4]

The primary fabrication method of optical fiber gratings involves utilizing the photosensitivity of optical fiber materials. This process involves exposing the core of the optical fiber to ultraviolet light to create a coherent pattern within the core. This exposure results in a periodic refractive index variation along the fiber's axis, forming a permanent spatial phase grating. Essentially, this grating serves as a narrow-band (transmissive or reflective) filter or reflector within the core. When a broad-spectrum light beam passes through an optical fiber grating, wavelengths that satisfy the Bragg condition of the grating will be reflected, while the remaining wavelengths continue to propagate through the grating.

The stability of the laser with a specific wavelength is ensured by the combination of front and rear cavity mirrors. Additionally, the cavity length is controlled during the fabrication process to meet the following formula.

$$v = \frac{qc}{2nL} \tag{1}$$

Here, v represents the laser frequency, q is a positive integer, L is the optical length of the cavity, n is the refractive index of the optical fiber, and c is the speed of light. Meeting this formula allows the formation of stable standing wave oscillations inside the cavity based on the fundamental principles of cavity resonance. These standing wave oscillations ensure that the laser remains confined within the resonant cavity and does not dissipate [5].

2.2. Wavelength Tuning

DBR (Distributed Bragg Reflector) mirrors consist of a continuous uniform grating. The laser wavelength is determined by the grating period and the effective refractive index of the waveguide. Wavelength tuning is achieved by altering the carrier concentration within the grating region through current injection, which subsequently modifies the effective refractive index. In integrated devices, waveguide gratings are typically fabricated using dual-beam interference exposure. Gratings on the same wafer have identical periods. DBR lasers employ Bragg gratings as mode-selecting filters, resulting in a fixed starting wavelength for tunable DBR lasers. To accommodate multiple DBR lasers with different starting wavelengths on the same wafer, it is necessary to produce waveguide gratings with varying periods. Clearly, low-cost dual-beam interference exposure methods are insufficient for this requirement [6]. Theoretically, electron beam lithography could produce gratings with arbitrary periods on the same wafer, enabling adjustment of the starting wavelengths for different DBR lasers. However, this approach is cost-prohibitive and low-yield, making it unsuitable for large-scale industrial production. Therefore, a four-segment DBR laser with a sampled grating is employed to achieve a broader range of wavelength tuning, offering promising applications.

Nevertheless, during the operation of lasers, inevitable temperature fluctuations affect various parameters of DBR lasers, including output wavelength, output power, and linewidth. This effect is especially pronounced in tunable lasers that use sampled gratings. When the Bragg grating is heated, heat flow induces quasi-periodic changes in refractive index along the Bragg grating, affecting the grating's modulation of wavelength. DBR-type tunable semiconductor lasers achieve wavelength tuning through current injection, allowing for rapid wavelength switching (on the order of nanoseconds). However, the electrically active part of a DBR tunable laser includes not only the active region but also the phase adjustment region and the grating modulation region, all of which generate heat when subjected to electrical current.

2.3. Resistance to Thermal Sensitivity

In the field of semiconductor laser technology, researchers in 2017 introduced a thermally isolated tunable DBR (Distributed Bragg Reflector) laser, along with its manufacturing method and utilization. The tunable DBR laser is composed of a front grating region, an active region, a phase adjustment region, and a rear grating region, all of which are sequentially coupled and grown on the same substrate. Between these regions on the substrate, isolation grooves are established based on the positions of the front grating region, active region, phase adjustment region, and rear grating region, creating partial isolation or independence among the substrate areas [7]. The inventive embodiment provides a substrate isolated DBR tunable laser, not only overcoming the conventional notion that the substrate must be a continuous entity but also effectively addressing the issue of heat interaction between various regions through the establishment of isolation grooves.

In 2021, Chinese researchers designed a driver and temperature control circuit for a DBR laser using MAX5113 and MAX1978 chips. Experimental results demonstrated that within 100 minutes, the stability of the output current for three channels reached 0.0254%, 0.00674%, and 0.0408%, respectively. The laser temperature exhibited a maximum fluctuation of 0.0058°C, ensuring the stability of the DBR laser's output wavelength. Additionally, the output wavelength of the laser could be tuned within the range of 1,544 nm to 1,553 nm [8].

3. Analysis of Application Scenarios

3.1. Optical Fiber Communication

In China, the use of DBR lasers for chaos-based synchronized key distribution in domestic optical fiber communication systems leverages the short reaction time and tunable properties of DBR lasers to achieve relatively low-latency communication key distribution. When the bandwidth of the chaos signal is around 12.5 Hz, a pair of parameters matched DBR lasers can be utilized for effective synchronized key distribution. Experimental evidence has shown that within a small parameter mismatch range, common noise can drive DBR lasers to achieve chaotic synchronization. The wavelength-keyed synchronization recovery time is approximately 6 ns. In a 160 km optical fiber link with dispersion compensation, key distribution with a bit error rate of 3.8×10^ (-3) and a final rate of 5.68 Mbit/s has been realized [9].

Another group of researchers discovered that distributed Bragg reflector lasers exhibit a larger frequency detuning range for generating chaos compared to ordinary semiconductor lasers. Moreover, when the frequency detuning exceeds 25 GHz, the energy of the generated chaotic signal concentrates in the low-frequency region, resulting in a flat spectrum. It was also observed that when noise light is injected into the main mode, high-dimensional chaos with a correlation dimension of 6 is generated, and the correlation dimension of chaos fluctuates significantly. Conversely, when noise light is injected into the side mode, the correlation dimension of chaos is approximately 2 and exhibits smaller fluctuations [10].

DBR lasers are also applicable in Optical Network Units (ONUs) within Passive Optical Networks (PONs). Researchers have explored the single-mode tuning characteristics, small signal response, and dual-mode lasing phenomenon of DBR lasers based on their wavelength tuning principles. They have

specifically focused on the application of DBR lasers in PON-ONUs, designing high-speed transceiver boards based on Field Programmable Gate Arrays (FPGAs) and conducting relevant experiments [11].

3.2. Medical Applications

Distributed Bragg Reflector (DBR) lasers find valuable applications in the field of healthcare and medicine. These lasers offer precise control over wavelength and can emit light with exceptional stability, making them indispensable tools for various medical applications. Here are some notable uses of DBR lasers in the medical sector:

DBR lasers are employed in various imaging techniques such as optical coherence tomography (OCT) and fluorescence microscopy. Their wavelength tunability allows researchers to fine-tune the laser for optimal imaging of specific tissues and biomolecules. This is crucial for non-invasive diagnosis and monitoring of diseases [12].

DBR lasers are utilized in dermatological procedures like laser skin resurfacing and tattoo removal. Their ability to produce specific wavelengths is crucial for targeting and effectively treating different skin conditions, while minimizing damage to surrounding tissue.

In ophthalmology, DBR lasers play a vital role in procedures like laser eye surgery (LASIK). Their precise wavelength control enables surgeons to reshape the cornea with high accuracy, correcting refractive errors like myopia, hyperopia, and astigmatism.

DBR lasers are used in PDT, a treatment for certain types of cancer and medical conditions. They activate photosensitizing agents in target cells, causing them to produce a cytotoxic form of oxygen that destroys nearby cancer cells [13].

Overall, DBR lasers contribute significantly to advancements in medical technology, enabling more accurate diagnoses, less invasive treatments, and improved patient outcomes in various healthcare disciplines.

3.3. Laser Sensing

The application of Fiber Bragg Grating (FBG) sensor systems has been widely adopted across various fields for real-time detection of multiple physical parameters, including pressure, stress, and temperature. An economically efficient design and implementation of an FBG sensor system based on narrowband Distributed Bragg Reflector (DBR) lasers and Field Programmable Gate Array (FPGA) demodulation technology have been reported. FPGA circuits are employed to control continuous wavelength scanning of narrowband DBR lasers, enabling high-speed data acquisition and processing for multiple channels. This cost-effective FBG sensor system, achieving a demodulation speed of 1 kHz and supporting 8 channels, paves the way for widespread applications of a simple and cost-efficient multi-channel FBG sensor system [14].

Researchers have documented the sensing and detection characteristics of refractive index changes in slotted DBR optical fiber lasers. Stability tests of slotted optical fiber lasers post-grooving were conducted, and experimental data were used to investigate the impact of different groove depths and widths on the beat frequency refractive index sensitivity. Experimental results indicate that as groove depth and width increase, the beat frequency exhibits larger drift when subjected to the same external refractive index changes, achieving a maximum refractive index sensitivity of -271.76 MHz/RI-unit. This structure is noted to enable simultaneous measurement of temperature and refractive index through multiplexing techniques [15].

4. Conclusion

In conclusion, Distributed Bragg Reflector (DBR) lasers have emerged as a versatile and highly valuable technology with a wide range of applications across various fields. Their numerous advantages, including high signal-to-noise ratios, narrow linewidths, and the ability to support distributed sensing, make them indispensable tools in scientific research and practical applications.

DBR lasers have been instrumental in a multitude of sensing applications, offering excellent performance in detecting parameters such as temperature, pressure, current, magnetic fields, and ultrasound. Their precise wavelength control and stability have enabled breakthroughs in fields like optical fiber communication, medical diagnostics, and chaos-based key distribution, revolutionizing how we collect data, conduct experiments, and address complex challenges.

As technology continues to advance, the potential for DBR lasers in sensing and detection applications is boundless. Researchers have explored innovative techniques, such as FPGA-based demodulation and slotted DBR optical fiber lasers, to further enhance their capabilities and adapt them to diverse environmental conditions.

With their proven track record and adaptability, DBR lasers hold significant promise for future developments in sensing technology. Their ability to provide accurate, real-time data across various parameters positions them as essential tools for addressing complex scientific, medical, and industrial challenges, and their continued exploration is certain to yield further exciting applications in the years to come.

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