論文の内容の要旨

論文題目　Design and Characterization of Silicon Photonic Crystal Waveguide for Optical Amplifier using Raman Scattering
(ラマン散乱効果を用いた光増幅器に向けたシリコンフォトニック結晶導波路の設計と評価に関する研究)

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Silicon photonics reveals a significant advancement in the development of integration with complementary metal–oxide–semiconductor (CMOS) electronics on silicon substrate. Most photonic devices on silicon substrate such as modulators, photo-detectors, and waveguides (WGs) have almost been fully demonstrated. However, the silicon-based light sources and amplifiers using electronic transitions are difficult to realize due to the indirect electronic band-gap of silicon. On the other hand, silicon offers a variety of nonlinear effects that can be utilized to achieve laser oscillation or light amplification. The optically pumped light amplifier and laser in silicon were first realized by using stimulated Raman scattering effect in 2001, which were demonstrated by using cm-long silicon wire WGs. Nevertheless, when we consider integrating this device into photonic-electric circuit, further miniaturization of the device size and reduction of the required optical pump power are still expected.

Photonic crystal (PhC) is an attractive structure for the purpose of making the device size small and improving the efficiency due to the property of slow light in PhCs, which can extend effective light-matter interaction time and thus nonlinear effect can be enhanced. In several researches, silicon PhC WGs have been designed for Raman scattering. The spontaneous and stimulated Raman scattering in silicon PhC WGs have been also observed experimentally. The main issue of these previous literatures is that a symmetric ultra-slow light mode to support pump light beam has not been designed, only the Stokes beam could operate in a symmetric ultra-slow light mode. To further enhance Raman scattering effect, slowing down both pump and Stokes beams is necessary for achieving breakthrough. In addition, using the symmetric modes both for pump and Stokes is favorable for the practical applications because they have high coupling efficiency from external fiber.

This dissertation concerns those research issues and presents original research works on design and characteristic of silicon PhC slow light WGs for Raman amplifiers. The main conclusions of this research are briefly described below.

We built our design model on PhC WGs, whose two guided modes provide low group velocities and small modal areas. The calculated Raman gain enhancement of the final optimized structure is 100 times larger than previous works.

When we take into account the possibility of applying our design structures to the future photonic-electric circuits, the devices are fabricated by CMOS-compatible fabrication process. Enhanced spontaneous Raman scattering in silicon PhC WGs due to the slow light effect have been observed from the fabricated devices. These are the first demonstrations of Raman scattering in silica-cladded PhC WGs, which are useful structures with their superior mechanical and thermal stability. We also observed stimulated Raman scattering in PhC WGs with modified holes under the CW excitation. To our best knowledge, this is also the first demonstration of stimulated Raman scattering in non-air bridge PhC structures. The result show a possibility that HSM PhC WGs could exhibit higher gain compared with the previous reports using air-bridge PhC WGs. We also measured signal amplification using stimulated Raman scattering through the PhC WG. The output of signal beam from the WG is increased with the simultaneous input of pump beams. This means that the amplification due to stimulated Raman scattering occurs in the PhC WG.

This dissertation is organized as follows.

Chapter 1 introduces the research background of silicon photonics, mainly the light sources for silicon photonics technology. Then, the motivation and objective of this dissertation are described.

Chapter 2 describes the fundamental physics of silicon Raman scattering. Following the basic theory, several researches of Raman lasers and amplifiers using photonic wire waveguides are introduced in this chapter.

Chapter 3 presents the basic theory of PhC structures. Due to the problem of large device size discussed in Chap. 2, some researchers have used PhC structures to enhance Raman scattering effect and reduce the device size. In this chapter, we first introduce the concept of PhC and the origin of the photonic bandgap. Then, we discuss two-dimensional PhC slabs that are commonly used structures for waveguides. We also briefly review the numerical calculation method to calculate the photonic band structures for PhC WGs. We explain the meaning of modes and bands of band structures by using an example of so-called W1 waveguide. Finally, recent researches about PhC nanocavities and waveguides for Raman scattering are reviewed in this section.

In Chapter 4, designs of silicon PhC slow-light WGs for Raman amplifier are discussed. First of all, the design rule and the figure of merit are defined. Following the design rule we designed two-dimensional PhC WGs with modified holes. In the last part of this chapter, the comparisons on performance among different designs is summarized and discussed.

The experiment characterizations of linear optical properties of silicon PhC slow-light WGs are presented in Chap. 5. To make sure our design structures compatible with future photonic-electric circuits, the devices are fabricated by CMOS-compatible fabrication process. Firstly, the merit of CMOS-compatible fabrication process and fundamental fabrication process are discussed in this chapter. The detail setup for linear transmittance measurement is explained here. Finally, we showed the characterization results of linear property in silicon PhC WGs.

Chapter 6 discusses experiment setups and characterization results of the Raman scattering in silicon PhC WGs. Enhanced spontaneous Raman scattering near photonic band edge of WG mode in silicon PhC WGs was demonstrated in the fabricated devices. Nonlinear increase of the Stokes power as a function of the pump power was also observed, which indicates the onset of stimulated Raman scattering. Furthermore, signal amplification using stimulated Raman scattering through PhC WGs is also reported. Analysis and discussion of amplification experiments using stimulated Raman scattering effect are also included.

Finally, Chapter 7 offers the conclusions and future outlooks for the work in this dissertation.