論 文 の 内 容 の 要 旨

論文題目　Investigation of Bloch surface waves on dielectric multilayers for photonic applications
（フォトニック応用のための誘電体多層膜におけるブロッホ表面波の研究）

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The surface wave-based applications have received great attention for their various optical properties and possibilities. Surface plasmon polariton (SPP) is one type of surface wave that can be excited at the interface between metal medium and dielectric medium. SPP has been investigated in a large variety of applications including biosensors, chemical sensors, microscopy, logic gate, and light switching. However, SPP-based applications are intrinsically limited in their practicality by severe ohmic losses occurring in their metal medium. The issue of short propagation lengths, limited operating wavelength, and narrow resonance prevent it from being used as part of the integrated photonic circuit (PIC). PIC offers significant advantages over electronic circuits, such as low-loss information transport and faster information processing.

Bloch surface wave (BSW), as another type of electromagnetic surface wave, BSWs propagate at the interface between a dielectric multilayer and the dielectric medium and are considered to be a dielectric analog to SPPs. BSW-based devices could circumvent the issues of SPP-based devices due to the low-loss propagation and wide operating wavelength regions owing to the metal-free structure. BSW has drawn a great deal of attention and has been studied widely for various applications including sensors, photodetectors, Mach−Zehnder interferometers, and components of photonic integrated circuitry in recent years. However, most of the studies of BSW focus on sensing applications, the study of on-chip integration photonic applications based on BSW are incomplete. The BSW-based on-chip integration photonic applications are promising for the development of low-loss and wide operating wavelength regions PIC.

To realized the BSW-based on-chip integration photonic applications, the manipulation of BSW on a chip is needed. The basic and important components, coupler and guiding slab are required for the manipulation of BSW. While the coupling of BSW by the grating coupler and the guiding of BSW by guiding-slab has been demonstrated in recent years, the demonstration of the integration of BSW-based grating coupler and guiding-slab is missing. In this study, the integration of BSW-based grating coupler and guiding-slab has been demonstrated, which opens the new possibility of BSW-based on-chip integration photonic applications. Furthermore, the sensing application based on the slab-guided BSW has been demonstrated in this study. Using metal-free structures that can serve as an efficient optical circuit with a long propagation length on a chip opens the new possibilities of the surface wave-based biosensor. This study will impact the development of analysis tools for label-free sensing for use in medical diagnostics, pharmaceutical research, and biological research.

Based on the slab-guided BSW, the all-optical logic gate has been proposed in this study. The all-optical logic gate devices have attracted enormous attention because of their critical applications in the fields of information processes and the development of PIC. There are various approaches to realize the all-optical logic gates such as the formation of constructive/destructive interference in the photonic-crystal structure and the guided-SPP. Although several types of logic gates are realized based on the photonic-crystal structure platform, the intrinsic instability and low extinction ratio between on and off-state hamper it to be used to build a practical photonic circuit. Though the SPP-based all-optical logic gate can overcome the issue of low extinction ratio, the intrinsic ohmic losses from electronic excitation in their metal medium have been seen as a bottleneck for building a practical photonic/plasmonic integrated circuit with low propagation loss. The proposed slab-guided BSW-based logic gate overcomes the issues of photonic-crystal-based and SPP-based all-optical logic gate. In this study, taking advantage of the metal-free structure and BSW interference-based mechanism, the proposed all-optical logic gate can be operated in telecommunication wavelengths with a high extinction ratio. Moreover, the long-distance waveguide-to-waveguide coupling is reached with a 100 um separation between two waveguides, which is almost 3 orders longer than that of the traditional evanescent waveguide-to-waveguide coupling with around a 250 nm separation has been demonstrated in this study.

The other application based on slab-guided BSW, light switching, has also been demonstrated in this study. As PICs include more individual optical elements and realize more complex functions, the ability to control the propagation direction of light is becoming important. Light switching based on spin-controlled unidirectional coupling has been demonstrated in chiral photonic circuits and SPP-based chiral-metasurface. Chiral-sensitive metasurface, as two-dimensional nanostructures composed of subwavelength elements that can arbitrarily control the propagation direction of electromagnetic waves through spin-controlled coupling, have drawn a lot of attention owing to its high directional selectivity. The ability to control the propagation direction and the operating wavelength of such structures through their shape and period makes them highly flexible. They, therefore, have the potential to facilitate the development of complex optical systems and PICs. However, the BSW-based chiral metasurface has not been demonstrated yet. In this study, the light switching based on BSW-based chiral metasurface has been demonstrated with high directional selectivity and long propagation length at telecommunication wavelengths. The ability to realize light switching on a chip at telecommunications wavelengths using the metal-free chiral-sensitive metasurface makes it promising for applications in low-loss on-chip photonic integrated devices and sensors.

The BSW-based applications have been widely studied as mention. However, most of these BSW platforms require a large number of layers to realize the coupling of the surface mode due to the small difference of refractive index between high- and low-refractive-index material. Additionally, although BSW modes have been investigated in the visible region and the near-infrared region, very limited reports are available for the mid-infrared region. MIR spectroscopy enables the determination of characteristic vibrational resonances of many functional molecules so that it can be used to perform label-free sensing, medical diagnostics, and food analysis. In this study, the BSW has been demonstrated both in NIR and MIR regions with the Ge/SiO_2 dielectric multilayer by adjusting the thickness of the dielectric layers of the BSW platform. The BSW mode was observed in the MIR range, thus greatly extending the range of BSW wavelengths and possibly reaching the fingerprint region of organic molecules.