様　式　C－19、F－19－1、Z－19　（共通）

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）誘導表面波プラットフォームによる超高感度・超高速光変調と多値・多重光処理の新展開

研究課題名（英文）Long-range guided surface waves with transverse spin and subwavelength confinement for optical switching and sensing

研究代表者
ＪＪ　Ｄｅｌａｕｎａｙ（DELAUNAY, Jean-Jacques）

東京大学・大学院工学系研究科（工学部）・准教授

研究者番号：８０３７６５１６

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研究成果の概要（和文）：強い空間的閉じ込め作用と長い伝搬距離を持つ表面波を発生、誘導、操作することは、センシングと光変調の最終目標である。従来、表面波の空間的閉じ込め作用は表面プラズモン波を用いて達成されてきたが、金属損失による短い伝搬距離が課題となっていた。本研究では、フォトニック結晶上に配置された極薄スラブガイドを用いたガイド付き表面波プラットフォームを提案する。特にトップダウン技術を用いて作製されたスラブガイドは、表面波の伝搬方向を制御するように設計されており、これらを組み合わせることで光論理ゲートを形成した。さらに利得材料で作られたスラブをパターニングすることで、同一チップ上に光源を集積することを実証した。

研究成果の学術的意義や社会的意義
A platform for surface waves was proposed with different functionalities. By controlling the shape and material of the slabs used to guide the surface waves, optical circuits can be patterned and used to perform various functions such as detection, optical logic operation, and coherent emission.

研究成果の概要（英文）：Generating, guiding, and manipulating surface waves with strong spatial confinement and long propagation lengths represents the ultimate goal for on-chip sensing and information processing. So far, spatial confinement of surface waves has been achieved using surface plasmon waves, but they suffer from short propagation lengths due to metal losses. Here, we propose a guided surface wave platform consisting of ultra-thin slab guides on a photonic crystal. We show that the proposed guided surface wave platform enables the fabrication and integration of various functional micro-components on a single chip. Particularly, slab guides fabricated by top-down technologies are designed to control the surface wave propagation direction and combine to form optical logic gates. Additionally, light sources are integrated on the same chip by patterning slabs made of a gain material.

研究分野：nano-optics

キーワード：surface wave　light confinement　coherent light source　optical sensing

１．研究開始当初の背景

Surface waves with fields that decay evanescently from material interfaces are powerful tools for manipulating electromagnetic radiation. At metal surfaces, the negative dielectric constant of metals allows for the existence of surface plasmon waves that couple electromagnetic radiation to electron oscillations near the metal surface. A wide variety of optical functionalities have been realized using surface plasmon waves. However, as a result of the inherent optical loss of metals, surface plasmon waves suffer from short propagation lengths and are ill-suited as a platform for large integrated systems with many components. Silicon waveguides, on the other hand, offer excellent propagation properties, but their photonic mode nature differs from that of a surface wave so that they have limited light confinement. The realization of guided surface waves with strong confinement and long propagation lengths through metal-free structures would represent a tremendous leap forward in the development of on-chip optical circuits with a high density of functional components. Using the Kretschmann configuration to excite a Bloch surface wave [1], the possibility of guiding the Bloch surface waves has been reported with the help of a top structure consisting of a polymer-resist ridge fabricated by photolithography [2]. Also, grating couplers have been demonstrated to couple radiation to surface wave modes without employing a bulky prism [3]. In the following, grating couplers are used to excite surface waves guided by slabs that are fabricated by top-down fabrication techniques such as lithography. Our group demonstrated the control of the propagation direction of these surface waves using the chirality of light polarization (left and right circular polarization of incident light results in propagation in opposite directions for the surface wave) at telecommunication wavelengths [4].

２．研究の目的

We propose to extend surface wave functionalities by designing guiding structures on a 1-D photonic structure and thus develop a surface wave platform with multiple functionalities such as light sources and interferometric devices realizing logic gate functions and sensing. Particularly, guiding structures in the form of thin slabs are microfabricated on top of 1-D photonic crystals with different shapes and materials to achieve various functions.

３．研究の方法

The guided quasi-Bloch surface wave modes are designed by calculating the dispersion diagram for a 2D system first and checking the mode behavior when the guiding structure on the top of the photonic crystal is added. As an example, the dispersion diagram for a mode in the visible along with the field distribution are given in Figure 1. The photonic crystal is fabricated by sputtering and the guiding structures are fabricated by lithography. Depending on the functions of the designed devices, different types of guiding structures have been proposed and realized using various processes such as lift-off process and or direct writing. For example, guiding structures made of silicon were fabricated to realize the optical logic gates and ring/disk made of doped resists were used for the fabrication of the coherent light sources.

The evaluation of the fabricated devices is performed using home-built microscopic setups where the excitation light can be adjusted on top of the structures using an objective lens and the device output is collected by the same objective lens. Two setups were built namely for the near-infrared region (telecommunication wavelengths) and visible region (demonstration of the coherent light source). Furthermore, a leakage microscopic setup was developed to collect the leaking light from the rear of the photonic crystal and analyze the angular distribution of light of the optical modes. This requires refractive index matching and a very large numerical aperture for the light collection and imaging in the Fourier plane to analyze the mode. Figure 2 gives the diagram of the setup used to perform the leakage radiation analysis in the visible range.

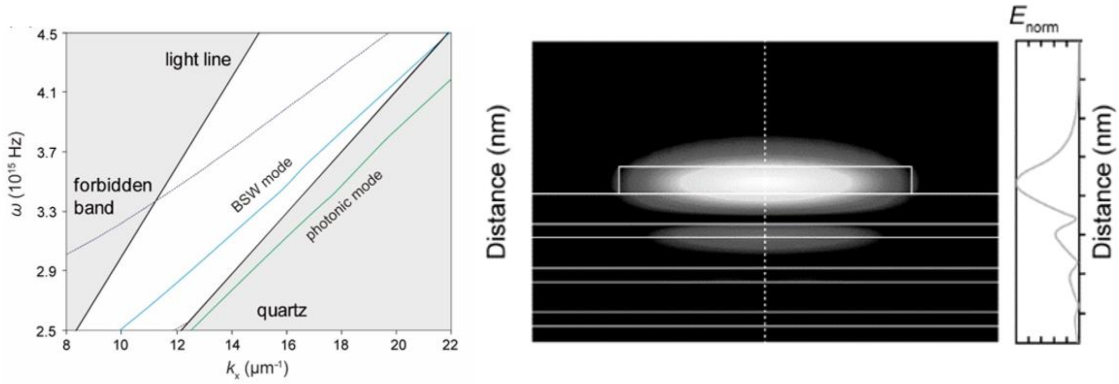

Figure 1: Typical (left) dispersion diagram and (right) electric field distribution of the Bloch surface wave mode.

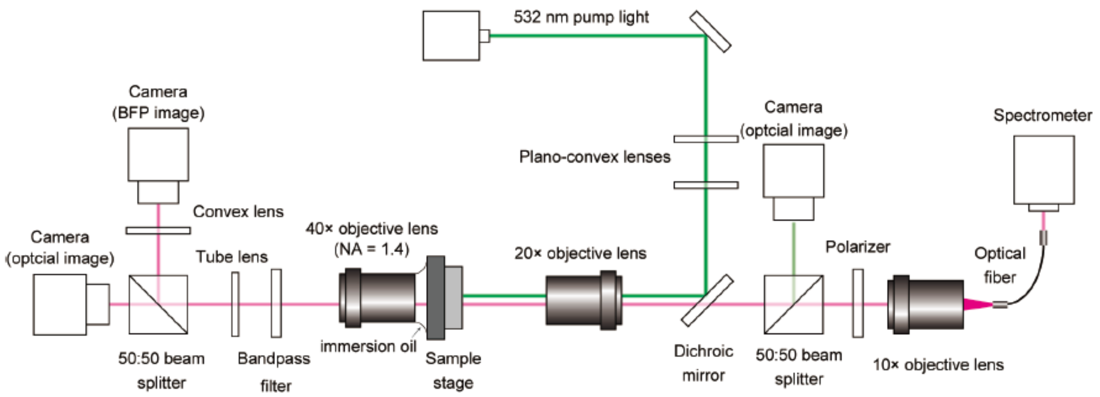

Figure 2: Leakage radiation analysis with Fourier plane imaging used to identify the optical modes.

4．研究成果

The results are summarized in the following steps: confirmation of the surface wave mode using leakage radiation, guiding structure with near zero index structure used to control propagation and realize logic gate functions, stimulated emission of a guided mode, and biosensing.

Evidence for the mode being excited is provided by leakage radiation in Figure 3. As these modes possess large effective refractive indices, they can be identified using this property. As shown in Figure 3, the mode used in the stimulated emission of the ring guided Bloch surface wave is found to possess a large effective index between 1.3 and 1.4 that matches the effective index value (1.36) of the designed mode.

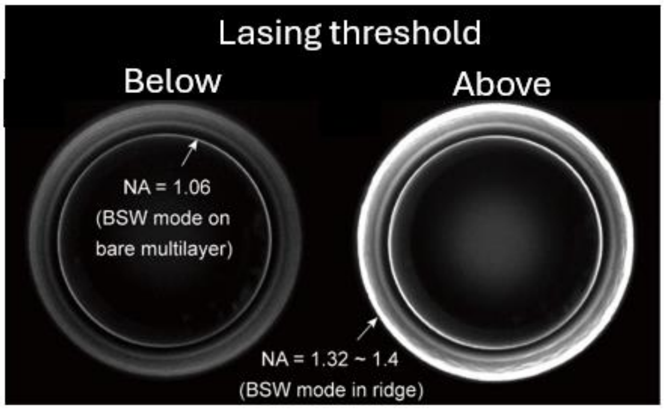

Figure 3: Leakage radiation analysis of the fabricated Bloch surface wave.

Leakage radiation analysis of the surface wave mode guided by a ring. The designed mode having an estimated effective refractive index of 1.36 is found to have an effective refractive index in the 1.32-1.4 range. This result was obtained for the stimulated emission of a guided Bloch surface wave mode using a ring as the guiding structure. The leakage from the guided Bloch surface wave appears as a ring in the large numerical aperture (NA) region. Both leakage distributions are shown for the cases corresponding to below and above the lasing threshold of the fabricated device [5].

The guiding structure fabricated on the top of the 1-D photonic crystal was designed to launch surface wave perpendicularly to the guiding structure using a near-zero index structure and devices were designed consisting of two inputs made of two guiding parallel but separated by a gap with an additional output structure in between the two input structures. By optimizing the separation gap and the position of the output structure in the gap, it was shown that different logic gates can be obtained. An XOR gate was fabricated and evaluated. This work was performed in the telecommunication wavelength range [6].

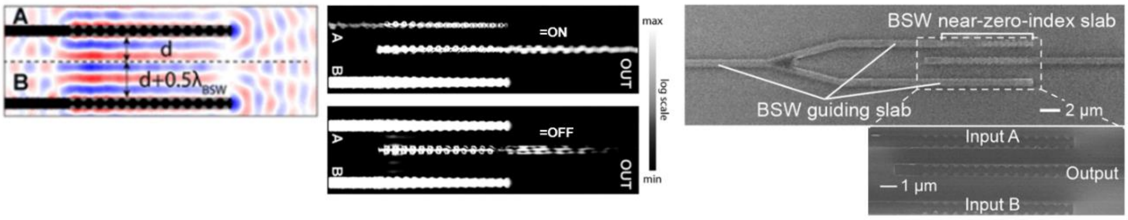

Figure 4: (left) Simulations of the XOR gate for the ON and OFF states. (right) SEM image of the top guiding structures consisting of two inputs and one output forming an all-optical XOR logic gate.

The guiding slab on top of the 1-D photonic crystal was made in the form of a resonator (ring) and made of an optical gain material (dye-doped resist) to achieve stimulated emission of a Bloch surface wave mode. For this purpose, a UV resist was doped with a dye and patterned in the form of a ring on top of the 1-D photonic crystal. Optical pumping of the doped-resist resulted in the observation of a non-linear variation in the intensity of the surface wave mode, that is, a lasing threshold was observed. Furthermore, the emitted radiation was analyzed with a spectrometer and showed a typical whispering gallery mode with very narrow emission [6].

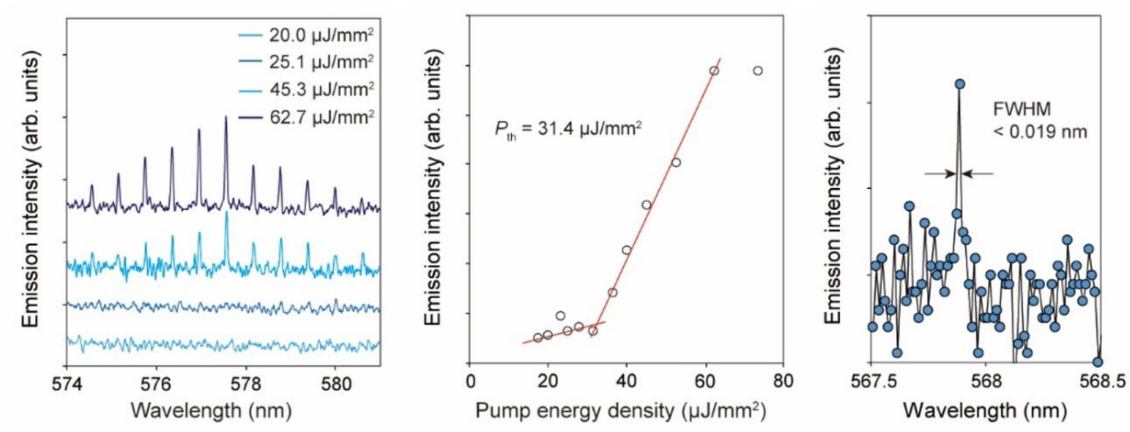

Figure 5: Observed emission, lasing threshold, and full width at half maximum of the stimulated emission of a doped-ring structure on a 1-D photonic crystal.

Another device was designed to detect biomaterials deposited on the surface wave platform. The detection of the biomaterials was investigated with an immunoassay based on BSA (antigen) and anti-BSA (anti-body), as shown in Figure 6. BSA immobilization on the surface induced a response in terms of a redshift. Subsequent reaction with anti-BSA further redshifts the response.

Fabrication techniques developed in the framework of this proposal have been applied to various optical designs such as for controlling the chirality of emitted light by incorporating 2D chiral material in an optical cavity [7] and achieving single-mode lasing from patterned structures sustaining a quasi-bound state in the continuum [8,9].

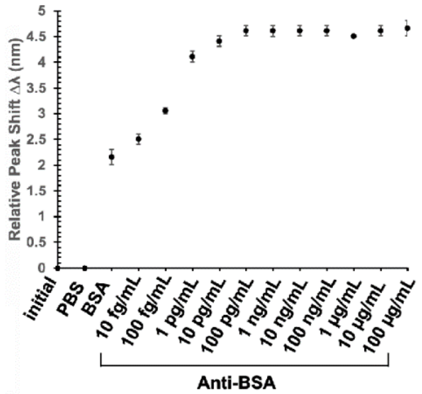

Figure 6: Sensitivity for the biomaterial detection.

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3．雑誌名 Nature Communications	6．最初と最後の頁 6458
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41467-023-41471-8	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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4．発表年
2021年～2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究分担者	何　亜倫 (HO Ya-Lun) (20815386)	東京大学・大学院理学系研究科（理学部）・特任助教 (12601)	
研究分担者	松井　裕章 (MATSUI Hiroaki) (80397752)	東京大学・大学院工学系研究科（工学部）・准教授 (12601)	
研究分担者	古川　克子 (Furukawa Katsuko) (90343144)	東京大学・大学院工学系研究科（工学部）・准教授 (12601)	

7．科研費を使用して開催した国際研究集会

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8．本研究に関連して実施した国際共同研究の実施状況

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