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Investigation of Bloch surface waves on dielectric multilayers for photonic applications

Ph.D. thesis defended by Deng Chih Zong

Surface waves with fields that decay evanescently from material interfaces are powerful tools for the manipulation of 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, such as spin-controlled light steering, light modulation, and bio-sensing, 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 (~50 microns) 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 and do not offer a means to control propagation direction by light spin properties.

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.

Deng proposes a guided surface wave platform consisting of ultra-thin slab guides on a photonic crystal. The proposed guided surface wave platform enables the fabrication and integration of a large number of functional micro-components on a single chip over a broad range of wavelengths. Detection of biomarkers, all-optical logic gates, and spin-controlled light steering are investigated. The thesis manuscript consists of six chapters.

In Chapter One, a review of the electromagnetic surface waves is first provided. The properties of surface plasmon polaritons and Bloch surface waves (BSWs) are described with an emphasis on the light confinement and propagation lengths of these two types of surface waves. If the surface plasmon polaritons enable very high light confinement at the interface between a dielectric layer and a metal layer, the propagation length is drastically limited due to metal losses. In contrast, the Bloch surface wave is confined near the interface between a dielectric layer and a one-dimensional photonic crystal and does not require any metal layer so that long propagation lengths can be achieved. Furthermore, the all-dielectric structure used to support BSWs can be easily scaled with the desired wavelengths thus offering potential applications in the near-infrared region for telecommunications and the mid-infrared region corresponding to the finger-print region of bio-molecules.

In Chapter Two, the strategy to guide BSWs on a chip is explained. BSWs are typically excited using Kretschmann's configuration which requires a bulky prism to match the momentum of the surface wave. Recently, it has been demonstrated that BSWs can be excited using grating structures microfabricated on the one-dimensional photonic crystal. Furthermore, guiding BSW using a slab on the one-dimensional photonic crystal has also been demonstrated. The combination of the grating launcher on a chip connected to BSW guiding structures is proposed by Deng. The design of the grating launcher is reported together with the guided mode, and the optimized structures are used to estimate theoretically and experimentally BSW propagation lengths at telecommunications wavelengths. A propagation length of about 130 μm is reported at a wavelength of 1.55 μm. Finally, the guided mode is used to detect biomarkers in a protein-ligand scheme consisting of a BSW guided mode interacting with the deposited bio-materials within a micro-fluidic channel.

In Chapter Three, the design of all-optical logic gates based on BSWs is proposed and partially demonstrated experimentally at telecommunications wavelengths. The functions of the logic gates AND, OR, and XOR are achieved using interferences of guided BSWs on a chip. A grating launcher is used to excite a mode guided by a slab that is connected to a near-zero-index slab that possesses an effective refractive index of approximately zero. The near-zero-index slab is used to launch BSWs on the one-dimensional photonic crystal. The combination of two near-zero-index slabs launching BSWs is used to form interferences and control the nature of the interferences, namely, constructive and destructive by the separation distance between the two near-zero-index input slabs. The inputs of the logic gates are made of these two near-zero-index slabs. The output of the logic gate is a third near-zero-index slab placed at the location corresponding to constructive or destructive interferences to couple out the BSWs. The XOR logic gate has a very high selectivity which has been verified experimentally.

In Chapter Four, the control of the BSW propagation direction by the polarization state of the incident light is demonstrated. To control the BSW propagation direction, a chiral launcher made of an array of U slits in the top layer on the one-dimensional photonic crystal is designed, optimized, and evaluated experimentally. A column of the U slits is designed to launch BSWs perpendicularly to the column with a phase difference between the left and right propagation directions. Exploiting the phase asymmetry, constructive and destructive interferences are realized depending on the light handedness. An array of the columns having a period corresponding to the BSW wavelength is then used to enhance the interference effect. Varying the spin angular momentum of the incident light results in the change in the propagation direction: circular left (right) polarized light couples to a guided surface wave propagating to the right (left) with selectivity as high as 26 dB theoretically and 13 dB experimentally.

In Chapter Five, taking advantage of the scalability of the structures supporting BSWs, the excitation of a broad range of BSW wavelengths from the near-infrared region to the important mid-infrared region for biosensing is investigated both theoretically and experimentally. It is noted that the excitation of such a wide range of wavelengths has not been reported for surface plasmon polaritons.

Chapter Six gives the general conclusion of the thesis.

In summary, Deng proposes a platform that supports guided surface waves over a broad range of wavelengths including telecommunications wavelengths and demonstrates integrated functional components such as all-optical logic gates (AND, OR, and XOR) as well as a surface wave launcher able to steer light in different directions depending on the incident light polarization. So far, these optical functions have only be realized using surface plasmon polaritons, which are known to have limited applications due to their short propagation lengths caused by metal losses. The above demonstrations are the first metal-free components with long propagation lengths that can control the light propagation direction as well as perform all-optical logic gate functions and as such have important technological implications.

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