UNIVERSITY OF CALIFORNIA SAN DIEGO

Spin-dependent Wave Propagation in Waveguides, Metasurfaces and 3D Photonic Crystals

A dissertation submitted in partial satisfaction of the
requirements for the degree
Doctor of Philosophy

in

Electrical Engineering (Photonics)

by

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Professor Yu-Hwa Lo
Professor George Papen

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The dissertation of Sara Kandil is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

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2022

DEDICATION

To my Mom and Sister, it wouldn't have been without you.

EPIGRAPH

Strange about learning; the farther I go the more I see that I never knew even existed. A short while ago I foolishly thought I could learn everything - all the knowledge in the world. Now I hope only to be able to know of its existence, and to understand one grain of it. Is there time?

—Daniel Keyes

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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PUBLICATIONS

Sara M. Kandil, Yun Zhou, Prabhakar Bandaru, D. Sievenpiper, ”*Screw dislocation in 3D Diamond photonic crystal for spin-dependent wave propagation*,” *In preparation*.

Sara M. Kandil, D. Bisharat, D. Sievenpiper, ”*C-shaped metasurface for polarization-based surface wave steering*,” *In preparation*.

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Sara M. Kandil, Anna Alexander, Kevin Jensen, Prabhakar Bandaru, Daniel F. Sievenpiper, Nathan A. Moody, ”*Photo-controlled solid-state negative hydrogen ion source*,” SPIE Photonics West 2022, San Francisco

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Sara M. Kandil, ”*Metasurfaces for spin-control of surface waves*,” Rising Stars in EECS workshop.

Sara M. Kandil, D. Bisharat, D. Sievenpiper, ”*Spin-momentum Locking of Chiral Surface waves*,” Metamaterials, October 2020

Sara M. Kandil, D. Bisharat, D. Sievenpiper, ”*C-shaped metasurface for polarization-based surface wave steering*,” SPIE Optics and Photonics: Metamaterials, Metadevices, and Metasystems, Aug 24-28, 2020

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Mai O. Sallam, **Sara M. Kandil**, Vladimir Volski, Guy A. E. Vandenbosch, and Ezzeldin A. Soliman, “*Flexible Bow-Tie Antenna for WLAN/Wi-Max Applications*” European Conference for Antenna and Propagation (EuCAP), Davos, Switzerland, April 2016.

Mai O. Sallam, **Sara M. Kandil**, Vladimir Volski, Guy A. E. Vandenbosch, and Ezzeldin A. Soliman, “*2.4/5 GHz WLAN crescent antenna on flexible substrate*” European Conference for Antenna and Propagation (EuCAP), Davos, Switzerland, April 2016.

ABSTRACT OF THE DISSERTATION

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Photon spin has received great interest in the recent decades for many applications such as encoding quantum information and spin-filtering. However, very little is known about controlling the direction and properties of the spin. It was recently found that surface waves with evanescent tails possess an inherent in-plane transverse spin which is dependent on the propagation direction.

In this dissertation, we investigate different 1D, 2D and 3D designs that support strong spin-dependent propagation. Starting with a 1D C-shaped waveguide, we show that the spin-density can be enhanced through dipole-to-dipole coupling resulting in highly directional wave propagation. We then show spin-dependent wave splitting in 2D metasurface by engineering the equifrequency contours. We demonstrate the possibility of steering the surface wave along curved

paths. We also introduce a new type of surface wave called a chiral surface wave which has two transverse spins, an in-plane one that is inherent to any surface wave and an out-of-plane spin which is enforced by the design due to strong x-to-y coupling and broken rotational symmetry. We show that the two transverse spins are locked to the momentum providing a highly confined spin-dependent propagation. Similar chiral modes can be induced in 3D structures by introducing screw dislocation defect in a diamond photonic crystal.

Our study opens a new direction for enhancing and controlling the spin properties of electromagnetic waves through engineering the symmetry of shapes in 1D, 2D and 3D. This provides an additional degree of freedom to control the propagation direction as well as the transverse spin of electromagnetic waves.

Chapter 1

Introduction

1.1 Spin-Hall Effect and Spin-momentum Locking

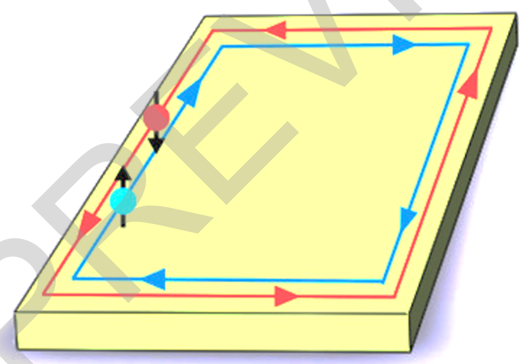

Figure 1.1: Spin Hall Effect in electronic systems (Source: [1]).

Spin is a universal property inherent to electrons and photons. Electron spin has been the origin of many intriguing phenomena such as Spin Hall Effect (SHE). SHE in electronic systems is characterized by the spin-dependent transport of electrons where electrons [2]. As shown in Fig. 1.1, a sample carrying electric current will have spin accumulation on its lateral surface where opposite spins propagate in opposite directions. This has opened the door for many applications in spintronics and quantum physics [3, 4]. It is also of great importance for providing platforms that can carry information with high robustness against defects which led to the discovery of topological insulators [5–8].

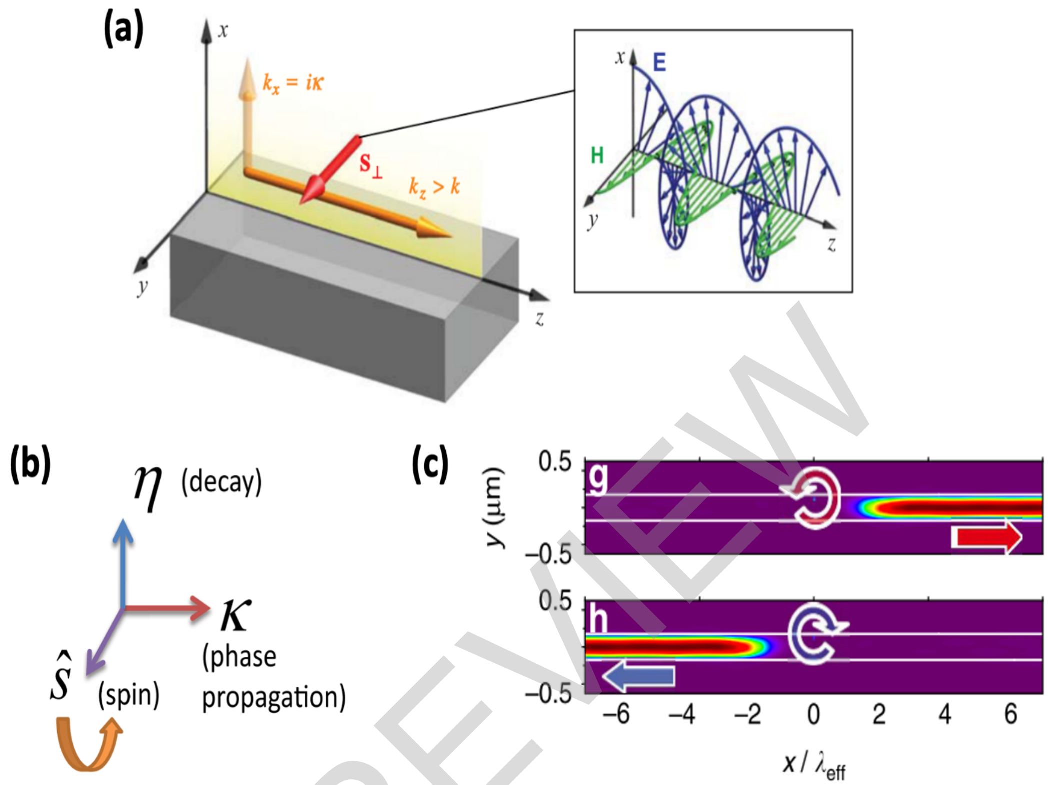

Figure 1.2: (a) Transverse spin for evanescent electromagnetic waves where spin represents E or H rotation (Source: [9]). (b) Schematic demonstrating spin-momentum locking formed of the right-hand triplet formed of Spin, decay constant and propagation constant (Source: [10]). (c) Demonstration of spin-dependent propagation where opposite handedness of CP wave propagate in opposite directions (Source: [11])

On the other hand, a photon's spin is associated with its polarization state, described as the handedness of its circular polarization (CP) where the spin vector is normal to the plane of the field rotation as illustrated in Fig. 1.2(a). Despite electrons and photons being fundamentally different particles, they reveal similar spin-related properties among which is the SHE. It was recently discovered that analogous to SHE in electrons, surface waves (SWs) with evanescent tails obtain an in-plane transverse spin (T-spin) that is locked to the propagation direction [9, 12, 13]. This is also known as spin-momentum locking which is defined as the right-hand triplet formed of the decay constant, spin and propagation constant [10, 14] as depicted in Fig. 1.2(b). Spin-momentum locking results in a spin-dependent propagation for the electromagnetic waves where opposite CP handedness propagate in opposite directions as shown in Fig. 1.2(c).

1.2 Spin density of Surface waves

In this section, we will go through the formulations for evaluating the spin vector obtained for any surface wave that has an evanescent tail and we will discuss their different properties. Consider the metasurface shown in Fig. 1.3 where a surface wave propagates along its interface in the $z-$axis direction. The normal to the surface is in the $x-$axis. Hence, the wave vector $\mathbf{k}$ is defined as: $\mathbf{k} = k_z\hat{\mathbf{z}} + i\eta\hat{\mathbf{x}}$, where the η is the decay constant of the evanescent tail of the surface wave which is pointed in the direction normal to the surface ($x - axis$). From Maxwell's equations, we can express the general E- and H-fields of this surface wave in Gaussian units as follows [15, 16]:

$$\mathbf{E} = \frac{A_0}{\sqrt{1+\|m\|^2}}\left(\hat{\mathbf{x}} + m\frac{k}{k_z}\hat{\mathbf{y}} - i\frac{\eta}{k_z}\hat{\mathbf{z}}\right)e^{ik_z z-\eta x}, \tag{1.1}$$

$$\mathbf{H} = \frac{\mathbf{k}}{k}\times\mathbf{E} = \frac{A_0}{\sqrt{1+\|m\|^2}}\left(-m\hat{\mathbf{x}} + \frac{k}{k_z}\hat{\mathbf{y}} + im\frac{\eta}{k_z}\hat{\mathbf{z}}\right)e^{ik_z z-\eta x}, \tag{1.2}$$

where A_0 is a constant representing the field amplitude and m is a complex polarization parameter [12, 15]. The spin density vector can be expressed in terms of E and H using the following equation [12, 16]:

$$\mathbf{S} = \frac{\mathrm{Im}\left\{\mathbf{E}^*\times\mathbf{E} + \mathbf{H}^*\times\mathbf{H}\right\}}{|\mathbf{E}|^2 + |\mathbf{H}|^2}, \tag{1.3}$$

where $\mathbf{S}$ is the vector spin density normalized per one photon in units $\hbar = 1$. By substituting the E and H expressions from equations 1.1 and 1.2, the different components of the $\mathbf{S}$ vector can be written as follows:

$$S_x = 0, \quad S_y = \frac{\eta}{k_z}, \quad S_z = \frac{2Im(m)}{1+\|m\|^2}\frac{k}{k_z}. \tag{1.4}$$