Research Statement

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Tailoring Evanescent Light on Surface

Program Summary. Gradient optical metasurfaces have been used to demonstrate a wavefront control of light in free space and in optical waveguides by imposing spatially varying optical responses to the light. However, the control of light localized and propagating on surface has been challenging because the surface waves scatter intensively to the metallic metasurfaces causing the optical loss. *Can we find new metasurfaces platform to tailor the surface waves of light?*

The program addresses the challenge by *understanding fundamentally the near-field interaction between surface waves of light and surface charge oscillations confined in gradient metasurfaces.* The PI chose polar dielectrics as an emerging metasurfaces platform displaying low optical loss and high coupling efficiency to the light. The PI classifies polar dielectrics into two types; Type-I bulk materials (e.g. SiC) and Type-II two-dimensional materials (e.g. h-BN) on which the evanescent field characters of surface waves are different.

The program focuses on three research projects; *Tailoring surface waves of light by (1) reconfigurable optical and thermal metasurfaces, (2) time-reversal symmetry-breaking metasurfaces, and (3) metasurfaces imitating quantum many-body systems.* The program benefits from developments in low-loss and high-performance plasmonic or photonic devices, spintronic devices, and flat optical devices working in the under-explored long-wavelength infrared.

The objectives of project 1 are to understand the collective surface oscillation of polarized ions and electromagnetic waves localized in Type-I and Type-II aperture antennas and to control the localized collective surface oscillation spectrally, spatially, and temporally under optical and thermal excitations.

The objectives of project 2 are to understand near-field interactions between surface waves and the time-reversal symmetry broken metasurfaces under an applied magnetic field and to manage non-reciprocal flow of light propagating and localized on the surface.

The objectives of project 3 are to construct artificial one-dimensional spin-chain systems with impurity states and to study quantum many-body system Hamiltonians with optical and electrical excitations.

Introduction. Metasurfaces, two dimensional optical nanostructures, have emerged in recent years as a platform for designing subwavelength scale optical components. Such designer optical interfaces introduce spatially varying optical responses such as phase, amplitude, polarization, and impedance which mold a wavefront of light [1-3]. Metasurfaces have been used to demonstrate a wavefront control of light in free space and in three-dimensional confined spaces such as linear and non-linear optical waveguides [4-5].

A control of light localized and propagating on two-dimensional surface has been challenging so far because of the high optical loss in metallic metasurfaces [6]. The surface waves can excite surface charges and form coupled modes of collective oscillation of charges and electromagnetic waves on surface. The coupled mode known as surface polaritons can be dissipated easily on the metallic surface. *Can we find new metasurfaces platform to tailor the light localized and propagating on surface?*

The PI chose polar dielectrics as an emerging metasurfaces platform displaying low optical loss and high coupling efficiency to the light in their optical phonon band as shown in Fig. 1(a). The polar dielectrics experience a polar optical phonon resonance exhibiting metal-like negative permittivity, which induces strong coupling with light but polarized ion oscillations result in the

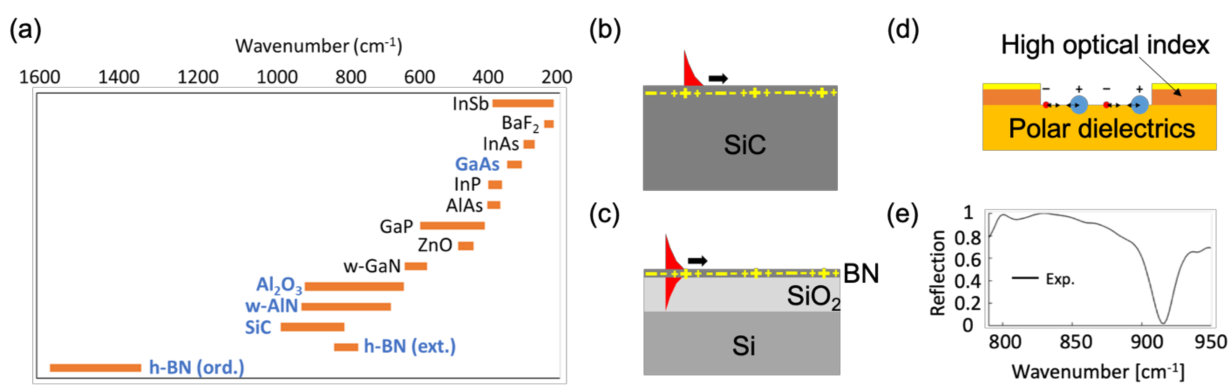

Figure 1. New metasurfaces platform to control surface waves of light. (a) Optical phonon band (red bar) of polar dielectrics at infrared. Materials of interest are highlighted in blue. (b)-(c) The PI classifies polar dielectrics in two types: (b) Type-I has one-side wing (red) of evanescent light (c) Type-II has wings (red) of evanescent light. Surface charge oscillations are indicated by yellow '+' and '-'. (d) Schematics of design. Soft boundary metasurfaces consisting of high optical index created by thin metal/dielectric multilayer apertures can confine surface phonon polaritons. (e) (preliminary data) Measured spectrum shows a single, well-defined, and strong resonance from the soft boundary metasurfaces on polar dielectrics.

low-loss character [6]. Coupled modes of collective oscillation of polarized ions and electromagnetic waves on surface is called surface phonon polaritons (SPhP).

The PI classified polar dielectrics in two types depending on the evanescent field characters of surface waves as shown in Fig. 1(b) – 1(c). When waves confined at surface, the amplitude of the wave decays exponentially away from the surface, which is called an evanescent field.

- Type-I: one-side wing of evanescent light, e.g. SiC, Al_2O_3, and GaAs.
- Type-II: wings of evanescent light, e.g. h-BN and h-AlN two-dimensional materials.

Figure 1(d) shows the preliminary antenna design using Type-I polar dielectrics which can be used as a building block of the SPhP metasurfaces. Thin aperture antenna design is the best candidate for polar dielectrics because the antenna only induces dipole resonance of the SPhP confined in a high-optical-indexed metal/dielectric multiplayer boundary.

Figure 1(e) shows a preliminary infrared spectrum of the Type-I (here, SiC) aperture antenna array displays a single, well-defined, and strong SPhP resonance to the infrared light. In this program, the PI will develop a Type-II (starting from h-BN two-dimensional material) aperture antenna, which will have more degree of freedom to control the surface waves of light depending on a character of the spacer layer, e.g. SiO_2 in Fig. 1(c).

Proposed Projects.

Project 1. *Tailoring surface waves of light by reconfigurable optical and thermal metasurfaces*

The objectives of project 1 are to understand the collective surface oscillation of polarized ions and electromagnetic waves localized in Type-I and Type-II aperture antennas and to control the localized collective surface oscillation spectrally, spatially, and temporally under optical and thermal excitations.

Project 1 benefits to develop a multifunctional building block for optical and thermal metasurfaces which can provide energy channels between phonons, electric charges, and photons through the collective oscillation on surface. The multifunctional building block offers many degrees of freedom for metasurfaces design which will open many potential applications.

Here is a list of specific research plans for achieving these objectives.

- *Plan 1: Development of Type-I and Type-II aperture antennas for metasurfaces*

  Design and fabrication of Type-I and Type-II antennas showing a single, well-defined, strong, and narrow-band resonance.

- *Plan 2: Spectral control of localized surface waves*

  Observation of near-perfect absorption, resonance spectral tuning, and photodetection by thermoelectric effect from optical metasurfaces, and narrow-band thermal emission spectral tuning from thermal metasurfaces.

- *Plan 3: Spatial control of localized surface waves*

  Development of flat optical components using gradient optical metasurfaces and narrow-band directional thermal emission using gradient thermal metasurfaces.

- *Plan 4: Temporal control of localized surface waves*

  Realization of reconfigurable resonance tuning by carrier injection using ultra short pulse Ti:Sapphire laser. Electron-hole creation and recombination rely on the time-scale of the pulse.

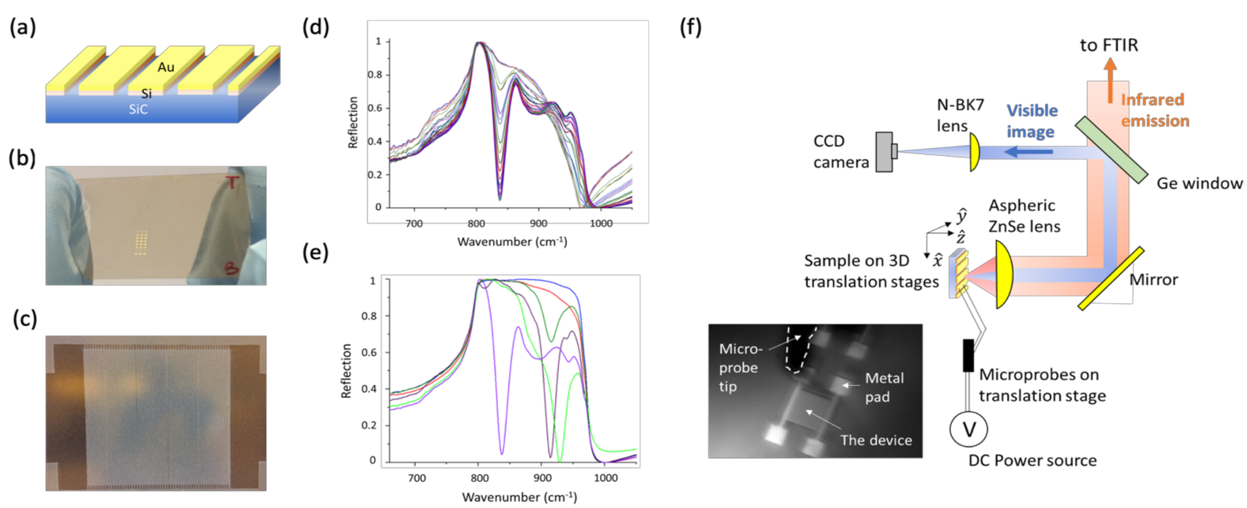

Figure 2. Preliminary optical and thermal metasurfaces. (a) Schematics of the device. (b) A picture of the device. Each bright spot shows 100 μm × 100 μm size device. (c) Scanning electron microscope image of the device. A square has 100 nm-scale gold/silicon multilayer aperture antenna arrays on SiC. U-shape patterns located top and bottom of the image are metal pad for electric connection to the device. (d) Polarization dependence of 100 nm-wide Au(40 nm)/Si(82 nm) aperture antenna grating with 900 nm period on SiC. (e) Resonance frequency tuning. Spectrum of SiC (blue), Si thin film on SiC (red), 100 nm-wide aperture antenna for 40-nm Au on top of 82-nm Si (light blue), 73 nm Si (black), and 67 nm Si (green) with 900 nm period on SiC. (f) Home-built thermal emission measurement setup. Optical path is shared with infrared light for collecting thermal signal and visible light (inset: CCD camera image) for pattern alignment and microprobe contact on metal pad.

Figure 2 shows the preliminary results for optical and thermal metasurfaces. Figure 2(a) – 2(c) shows a preliminary Type-I aperture antenna array serving as optical and thermal metasurfaces. Figure 2(c) shows 100 nm-scale metal/dielectric (Au/Si) multilayer aperture antenna arrays on Type-I polar dielectrics (SiC) which control 10 μm wavelength light. The scale of the antenna is deep sub-wavelength scale (~1/1000). The U-shape pattern connected to the antenna array is a metal pad for thermoelectric voltage measurement or electrical heating used in thermal emission measurement. Figure 2(d) shows polarization dependence of the device. The polarization perpendicular to the grating excites the surface phonon polariton resonance exhibiting near perfect absorption of the light. The reflectance increases when rotating the polarizer until the polarization is parallel to the grating. Type-I aperture antenna displays a single, well-defined, strong, and narrow-band resonance. Figure 2(e) shows the resonance frequency tuning in whole optical phonon band. Figure 2(f) shows home-built thermal emission measurement setup. Optical path is shared with infrared and visible lights for microprobe and the pattern alignment. The microprobe is used for heating only one device on the chip.

Project 2. *Tailoring surface waves of light by time-reversal symmetry-breaking metasurfaces*

The objectives of project 2 are to understand near-field interactions between surface waves and the time-reversal symmetry broken metasurfaces under an applied magnetic field and to manage non-reciprocal flow of light propagating and localized on the surface.

Project 2 will enable us to address numerous challenging topics in optics, including optical isolation, phase modulation, and angle rotation and ellipticity measurement standards.

Here is a list of specific research plans for achieving these objectives.

- *Plan 1: Installation of home-built infrared broadband Kerr microscopy*
  Development of a polarization rotation and ellipticity calibration standard. Spectral and spatial mapping of Kerr microscopy.
- *Plan 2: Investigation of optical non-reciprocity in an out-of-plane magnetic field*
  Development of Kerr angle rotation and ellipticity standard from the time-reversal symmetry broken metasurfaces.
- *Plan 3: Investigation of optical non-reciprocity in an in-plane magnetic field*

Development of optical isolator of the surface light on the time-reversal symmetry broken metasurfaces.

Figure 3(a) shows the schematic of a home-built infrared broadband Kerr microscopy system, which covers the mid-infrared spectral range (70 meV – 200 meV). This technique modulates the frequency and polarization of light simultaneously. Slow frequency modulation (~ a few kHz) is positioned in the side-band of fast polarimetry modulation (at 50 kHz). The fast signal is decoded by a lock-in amplifier and then the slow signal from the polarization is sent through a Fourier transform to obtain the rotation and ellipticity spectrum. Figure 3(b) shows preliminary rotation calibration. The angle rotation spectrum shows 1 deg from 800 cm^{-1} to 1400 cm^{-1} when the first polarizer in Fig. 3(a) rotates 1 deg. The resolution of this technique is easily achievable to 1 mrad, which is a good fit to an angle measurement for ferromagnetic samples. Figure 3(c) shows a schematic of the proposed non-reciprocal metasurfaces made of magnetite aperture antennas on polar dielectrics. Surface waves of light are essentially polarized in a transverse magnetic (TM)

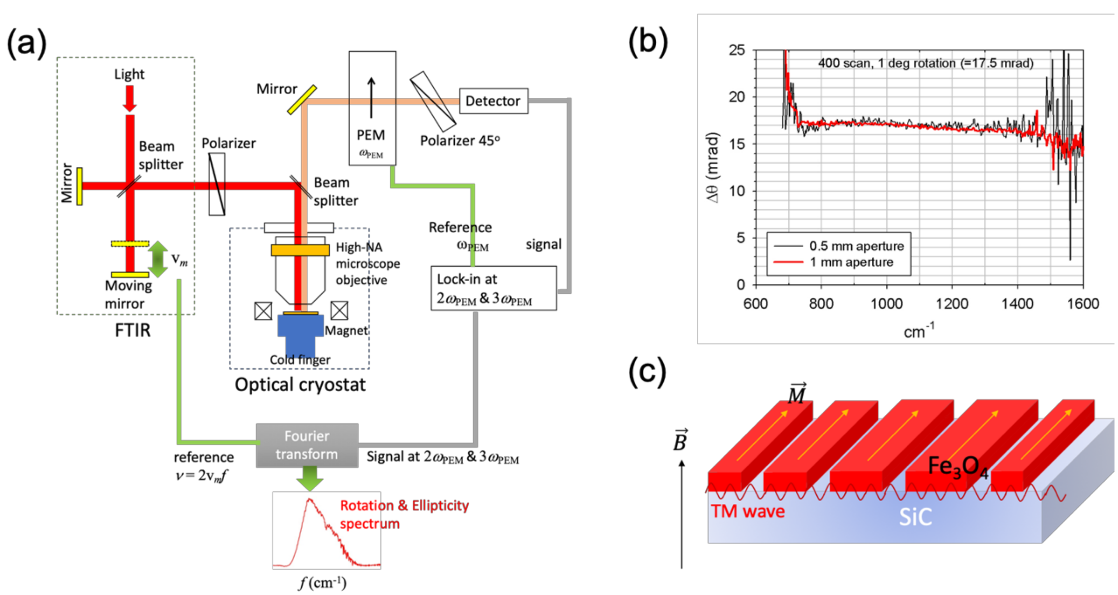

Figure 3. Non-reciprocal metasurfaces. (a) Schematic of home-built infrared broadband Kerr microscopy system. Double modulation technique is used to measure Kerr angle using broadband light source. Second and third harmonic signals of photoelastic modulator (PEM) frequency carry rotation and ellipticity spectral information respectively, which can be decoded by Fourier transform at the reference frequency ν determined by mirror speed v_m and the frequency of light f (b) (preliminary data) Frequency reliability of rotation signal of 1 deg. When rotating polarizer 1 deg, mid-infrared spectrum shows 17.5 mrad which corresponds to 1 deg. (c) Schematic of the proposed device. Magnetite (Fe_3O_4) boundary is slightly magnetized by transverse magnetic (TM) surface waves of light. Under application of magnetic field, the magnetization will be disturbed.

field. Under the illumination of light, TM surface waves induce magnetic domain alignment, which will rotate when the magnetic field is applied. Since the refractive index of left (n_L) and right (n_R) circularly polarized light are slightly different, Kerr angle rotation (θ_K) results in

$$Re[\theta_K] \propto n_L - n_R \propto I_{2\omega_{PEM}},$$

where $I_{2\omega\text{PEM}}$ is the second harmonic signal of the photoelastic modulator frequency, which carries the angle rotation information.

Project 3. *Tailoring surface waves of light by metasurfaces imitating quantum many-body systems*

The objectives of project 3 are to construct artificial one-dimensional spin-chain systems with impurity states and to study quantum many-body system Hamiltonians with optical and electrical excitations.

Project 3 benefits to solve quantum many-body system Hamiltonians by mimicking the system using artificial nanostructures. In addition, the proposed metasurfaces are good platforms to study low-dimensional quantum systems, a few of which can be solved exactly.

Here is a list of specific research plans for achieving these objectives.

- *Plan 1: Type-I spin-lattice chain*

  Demonstration of Ising ferromagnetic spin model.
- *Plan 2: Type-I spin-lattice chain with localization mode*

  Demonstration of impurity modes in a one-dimensional periodic system. Investigation of impurity band in photonic band gap.
- *Plan 3: Type-II spin-lattice chain with/without localization mode*

  Demonstration of spin-lattice-impurity modeling with an enhancement of the coupling between neighbors.
- *Plan 4: Type-II spin-lattice chain with guided light*

  Demonstration of spin-lattice-impurity modeling with an interaction with guided light in a spacer layer.

Figure 4(a) shows a schematic of a Type-I spin-lattice chain under an applied electric field. The model Hamiltonian will be

$$H = -J \sum_{i=1}^{N-1} \sigma_i \sigma_{i+1},$$

where J is the coupling coefficient between neighbor spins, i is lattice index, N is total number of spin sites, and σ_i is the spin state on the ith lattice site. Figure 4(b) shows preliminary data for a 2nd order phase transition of reflection from the model device. An applied electric field is created by a voltage difference across the pattern. When increasing the voltage, reflection jumps up, caused by spontaneously symmetry breaking of the spin system due to the long-range order parameter, which presents a second-order phase transition at the critical point. Many other quantum systems can be created, including Type-I spin-lattice chains with localization mode, as shown in Fig. 4(c), Type-II spin-lattice chains enhancing interactions with neighbors, as shown in Fig. 4(d), and Type-II spin-lattice chains with an interaction with guided light in a spacer layer, as shown in Fig. 4(e).

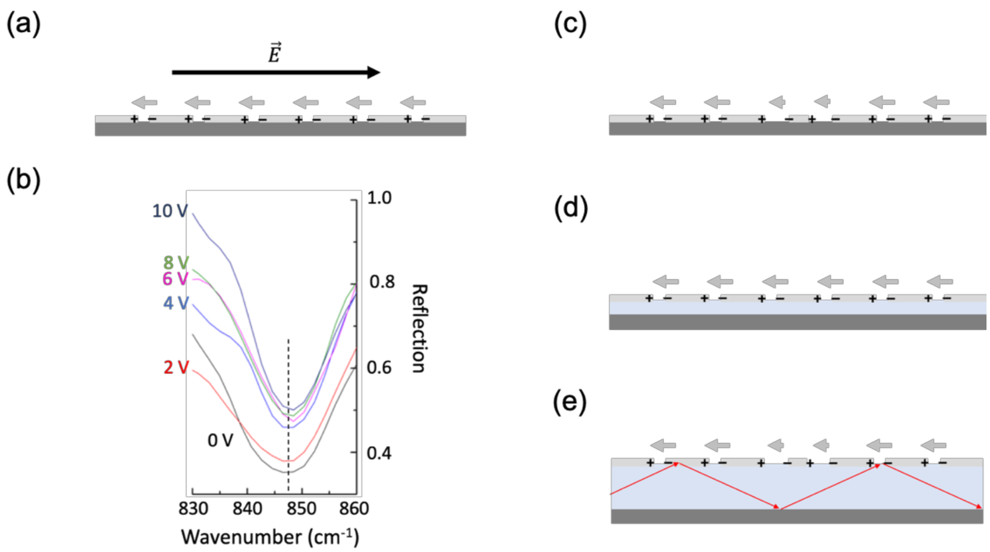

Figure 4. (a) Schematic of Type-I spin-lattice chain under an applied electric field. Gray arrow is electric dipole moment. (b) (preliminary data) 2nd order phase transition of reflection at resonance frequency is observed because spin-lattice chain can be explained by Ising ferromagnetic spin model. (c) Schematic of Type-I spin-lattice chain with localization mode. (d) Schematic of Type-II spin-lattice chain. (e) Schematic of Type-II spin-lattice chain with localization mode interacting with a guided light in spacer layer.

Budget Justification for Major Instrumentation

Mid/Far infrared spectroscopy and microscopy system	
Infrared Fourier Vacuum Spectrometer VERTEX 70v-FM, Bruker	$127,187
Infrared Microscope HYPERION 2000, Bruker	$72,100
Ultra-short pulse laser system	
Ti:Sapphire laser system, Coherent	$121,900
Low-temperature measurement system with electromagnet	
Cryostation with magneto-optic module, Montana Instruments	$126,800
Home-build infrared broadband Kerrr microscopy system	
ZnSe Photoelastic modulator, Hinds Instrument	$14,290
High-NA microscope objectives	$6,000
Vacuum nano-positioning for microscope	$13,322
Sensitive optical detection system	
MCT Detector FTIR-24-1 for mid infrared, Infrared Associates, Inc.	$3,325
Standard 4.2K bolometer for far infrared, Infrared Lab.	$23,495
Two DSP dual phase lock-in, Standard Research Systems.	$11,100
Three motorized stages with stepper motor controller, Thorlabs.	$9,591
Optomechanics and parabolic mirrors, Thorlabs (estimated cost)	$30,000
Home-build thermal emission measurement system	
All optical components from Thorlabs	$5,141
Optical Tables	
Two optical tables, TMC	$20,000
Full-wave simulation	
Lumerical FDTD simulation package (academic, basic, 5 years)	$6,000
Total:	**$590,251**

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