Effect of grating period on the excitation of multiple surface-plasmon-polariton waves guided by the interface of a metal grating and a photonic crystal

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ABSTRACT

The excitation of multiple surface-plasmon-polariton (SPP) waves guided by the interface of a metal and a one-dimensional photonic crystal in the grating-coupled configuration was studied both experimentally and theoretically. Only *p*-polarized incident light was considered in the visible and near-infrared regimes. When the absorptance was plotted against the angle of incidence, the excitation of an SPP wave was indicated by an absorptance peak whose angular location did not change with the number of periods (beyond a threshold) of the photonic crystal. A decrease in the period of the metal grating resulted in shifting the excitation of the SPP waves to smaller wavelengths.

Keywords: surface plasmon-polariton wave, photonic crystal, grating-coupled configuration, photovoltaics

1. INTRODUCTION

A surface plasmon-polariton (SPP) wave is an evanescent surface wave whose propagation is guided by the interface of a metal and a dielectric material.[1] SPP waves have been studied intensively in recent years for a wide range of potential and actual applications such as chemical sensors,[2] biological sensors,[3] photovoltaics,[4-7] photo-electrochemical cells,[8] solar fuel production,[9] and solar thermal photovoltaics.[10]

Both the metal and the dielectric material are conventionally taken to be homogeneous. SPP waves can only be excited by *p*-polarized light when light is incident parallel to the grating vector of a one-dimensional (1D) metallic grating.[1] Furthermore, only a single SPP-wave mode can be excited at a specific free-space wavelength λ_o. The excitation of only a single *p*-polarized SPP-wave mode seriously limits this techinique from being a viable choice for enhancement of light harvesting in solar cells, because incident *s*-polarized light is inefficiently used. Our recent theoretical[11] and experimental[12] studies have shown that multiple SPP-wave modes of both linear polarization states can be excited at the interface of a 1D gold grating and a 1D photonic crystal. Gold gratings with a fixed period but different depths and duty cycles were used to excite multiple SPP-wave modes. As expected, the absorptance of the metal-grating/photonic-crystal structure is highly sensitive to the grating profile. We present here the results of our investigations on the effect of grating period on the excitation of multiple SPP-wave modes.

2. MATERIALS AND METHODS

Gold gratings were fabricated as described in detail elsewhere.[13] In brief, ZEP520A photoresist (Zeon,Tokyo) was spin cast onto a silicon wafer at 4000 rpm. The silicon wafer was then patterned by electron-beam lithography at 100 keV on ZEP520A photoresist and developed in N-amyl acetate for 180 s, followed by immersion in a solution of isopropanol:methyl iso butyl ketone (8:1) and then rinsing with water. After development, the photoresist yielded the inverse pattern of the desired gold grating. The pattern in the photoresist was transferred to a silicon wafer by inductively coupled reactive ion etching on a Versalock 700 (Plasma-Therm, St. Petersburg, FL) with pure chlorine

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gas flowing at a rate of 40 sccm for 60 s. The photoresist was then dissolved in nanostrip, a commercialy available resist stripper. Gold was thermally evaporated onto the patterned silicon wafer at 1 A/s deposition rate. A drop of EpoTek 377 epoxy (Epoxy Technology, Billerica, MA) was placed on the patterened gold film. A glass slide was placed on top of the epoxy resin drop. The epoxy resin was cured in the oven for 1 h at 125 ºC. The patterned gold film was released from the silicon wafer with a razor blade, thereby yielding a gold grating glued to a glass slide. Line scans on an atomic force microscope (AFM) of two gratings are presented in Fig. 1.

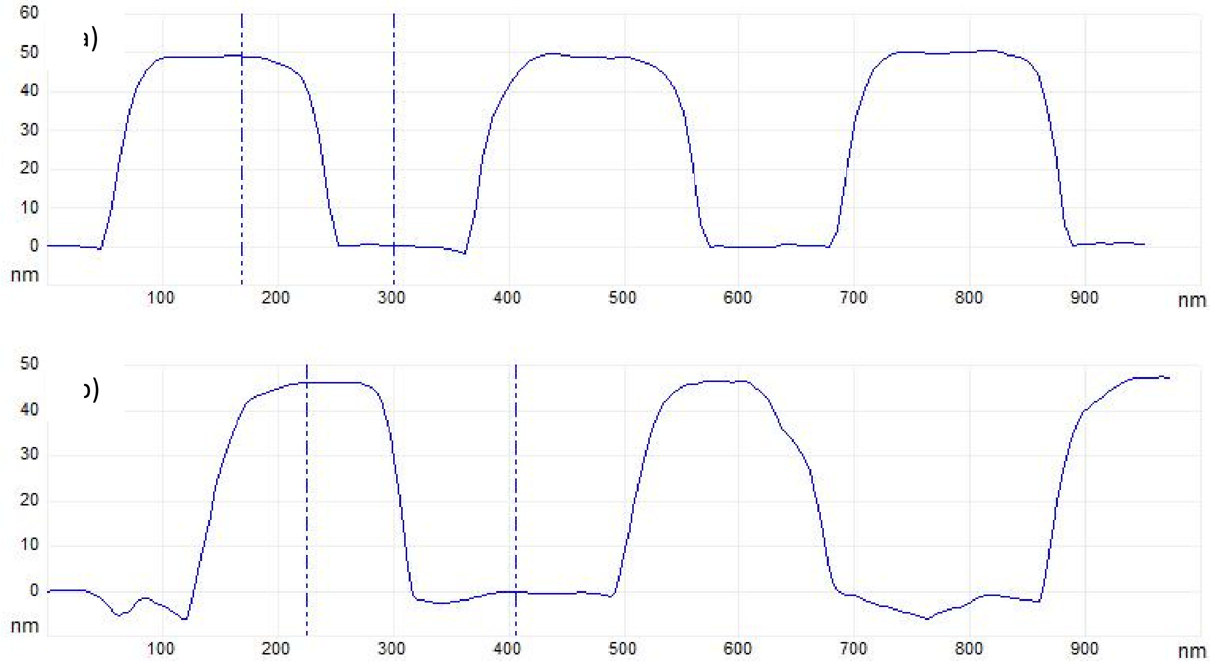


Figure 1. AFM line scans of gold gratings with a period of (a) ~300 nm and (b) ~350 nm.

Silicon oxynitride layers were grown by plasma-enhanced chemical vapor deposition on a Cluster Tool (Applied Materials, Santa Clara, CA) at 220 ºC directly onto gold gratings. Ammonia, silane, and nitrous oxide were used in varying ratios to deposit the layers with specific refractive indexes. The cross-sectional image on transmission electron microscope (TEM) of a three-period-thick photonic crystal backed by a gold grating is shown in Fig. 2. The AFM line scans were collected on a Digital Instruments 3100 AFM (Digital Instruments, Tonowanda, NY), and the TEM image was collected on a Phillips 420 TEM (Phillips, Amsterdam, The Netherlands).

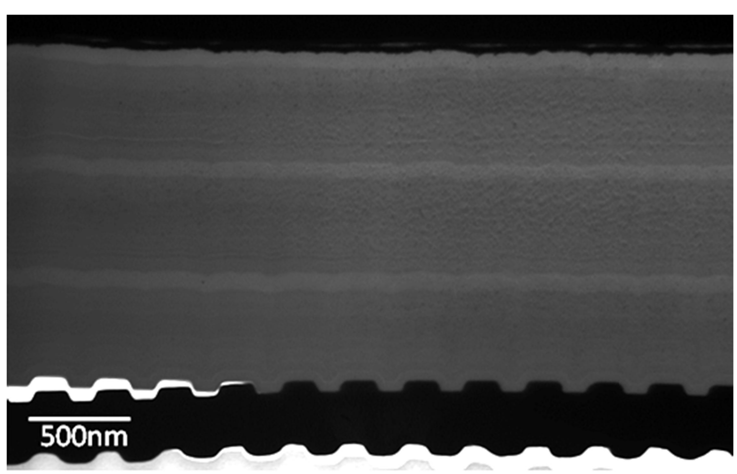


Figure 2. TEM image of a cross-section of a three-period-thick photonic crystal backed by a gold grating with a period of ~300 nm. The thickness of each dielectric layer in the photonic crystal is ~52 nm except for the ninth layer in each period, which is ~80 nm in thickness.

The refractive index of every layer, whether dielectric or metallic, was measured with an RC2 spectroscopic ellipsometer (Woollam, Lincoln, NE) as a function of λ_o. For that purpose, a layer of the specific material was deposited on either a glass slide or a polished silicon wafer. The measured relative permittivities of all nine dielectric layers present in the photonic crystal are presented in Fig. 3(a), and that of gold in Fig. 3(b).

Reflectance measurements were performed on a Lambda 950 UV-Vis (Perkin Elmer, Waltham, MA) with a Universal Reflectance Accessory. Measurements were performed in steps of 1 nm for λ_o and 1° for the angle of incidence θ.

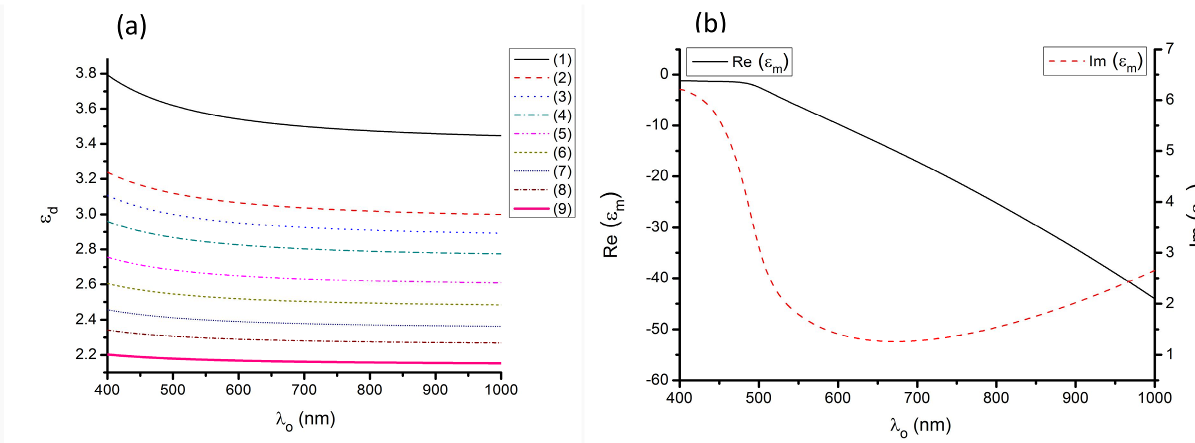
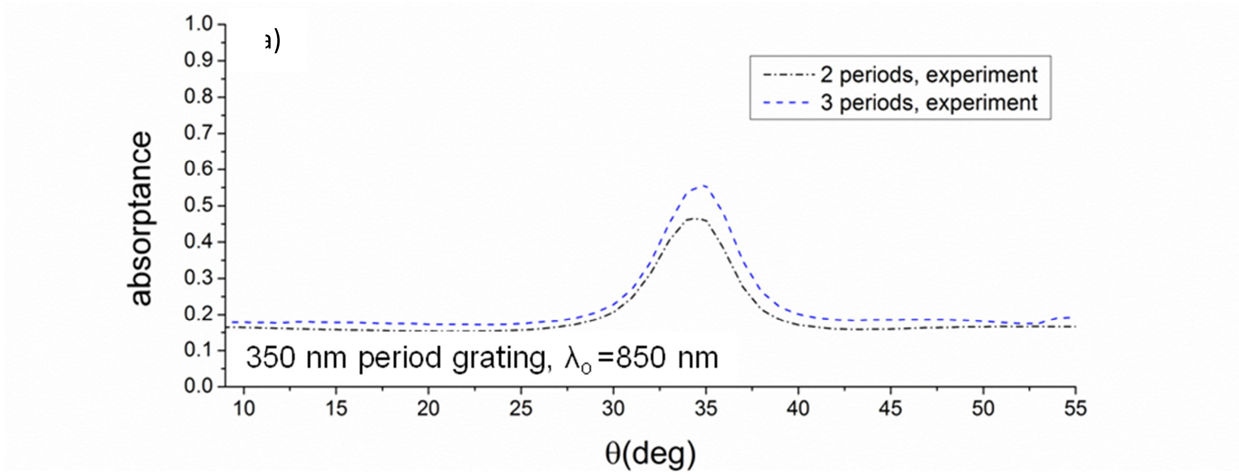


Figure 3. (a) Relative permitivity as a function of λ_o of all dielectric layers; the label (1) denotes the layer closest to the metal grating, the label (9) denotes the layer farthest away from the gold within a given period, and the intermediate layers are numbered in the order in which they appear betwen layers labeled (1) and (9). (b) Real and imaginary parts of the relative permittivity of an optically thick gold film as a function of λ_o .

3. RESULTS AND DISCUSSION

The specular reflectance R_{0p} and the total reflectance R_p of a photonic crystal backed by a gold grating were calculated for *p*-polarized incident light using the rigorous coupled wave approach (RCWA),[11] when the period of the grating was 308 nm. The number of terms in the expansion of field phasors in terms of Floquet harmonics and that of the permittivity as a Fourier series was taken to be 31. The protuberances of the grating were taken to be of sinousoidal shape. According to the calculations, the non-specular components of the total reflectance in the considered spectral regime were very small and the metal grating was thick enough to prevent transmission across itself; therefore, the absorptance $A_p = 1–R_{0p}$. As previous work[12] has shown that the gratings with protuberance near 50 nm in height (as is the case in this work) do not assist in the excitation of *s*-polarized SPP-wave modes, calculations were not made for *s*-polarized incident light.

The measured absorptance A_p is plotted in Fig. 4 as a function of the angle of incidence θ, when the period of the grating is either ~300 nm or ~350 nm, and $\lambda_o = 850$ nm. As the peak at $\theta \cong 35^o$ in Fig. 4(a) is independant of the thickness of the photonic crystal, it represents the excitation of a *p*-polarized SPP-wave mode. However, no waveguide modes or SPP-wave modes are excited when the period of the grating is 300 nm because no absorptance peaks are present in Fig. 4(b).



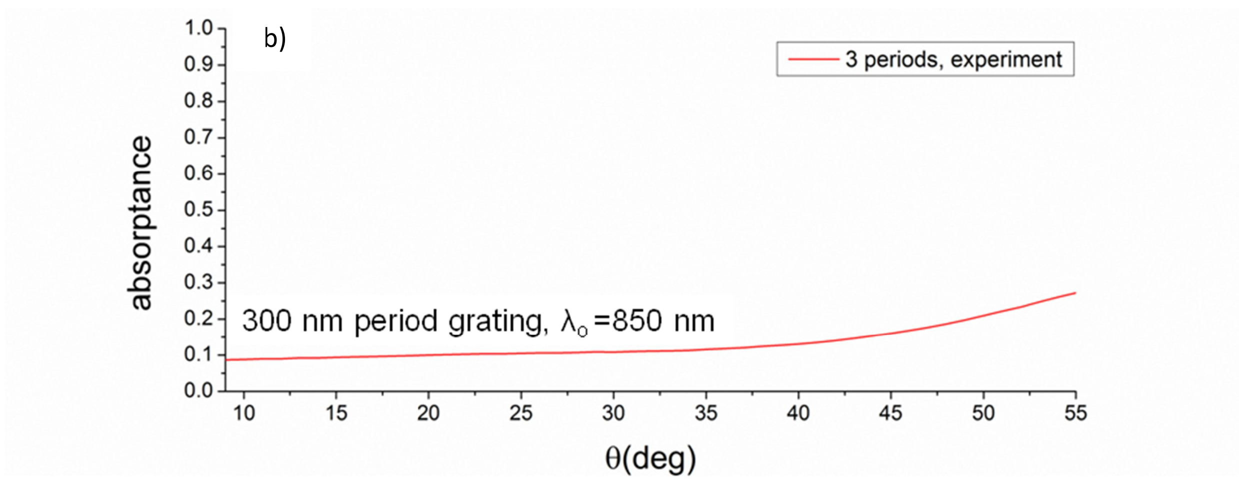


Figure 4. Measured absorptance A_p as a function of the angle of incidence θ of two- and three-period-thick photonic crystals each backed by a gold grating with a period of (a) 350 nm and (b) 300 nm, when λ_o = 850 nm.

The measured absorptance A_p as a function of θ is plotted in Fig. 5 when λ_o = 650 nm and the period of the grating is either ~300 nm or ~350 nm. When the grating period is 350 nm, two peaks at $\theta = 17^o$ and 23^o are present in Fig. 5(a), whether the photonic crystal has two periods or three. These peaks must be due to the excitation of *p*-polarized SPP-wave modes. When the period of the grating is ~300 nm, only one SPP-wave mode (at $\theta = 41^o$) is excited. Let us note the fairly good match between the calculated and measured absorptance in Fig. 5(b) except that the sharp peaks present in the calculated-absorptance plot were absent in the measured-aborptance plot, and the peak at $\theta = 41^o$ in measured-absorptance plot is slightly shifted to a higher value in the calculated-absorptance plot. These differences between experimental and theoretical data are expected because RCWA assumes a periodic variation along the direction of propagation of SPP waves; however, the actual fabricated grating is somewhat different in each period.

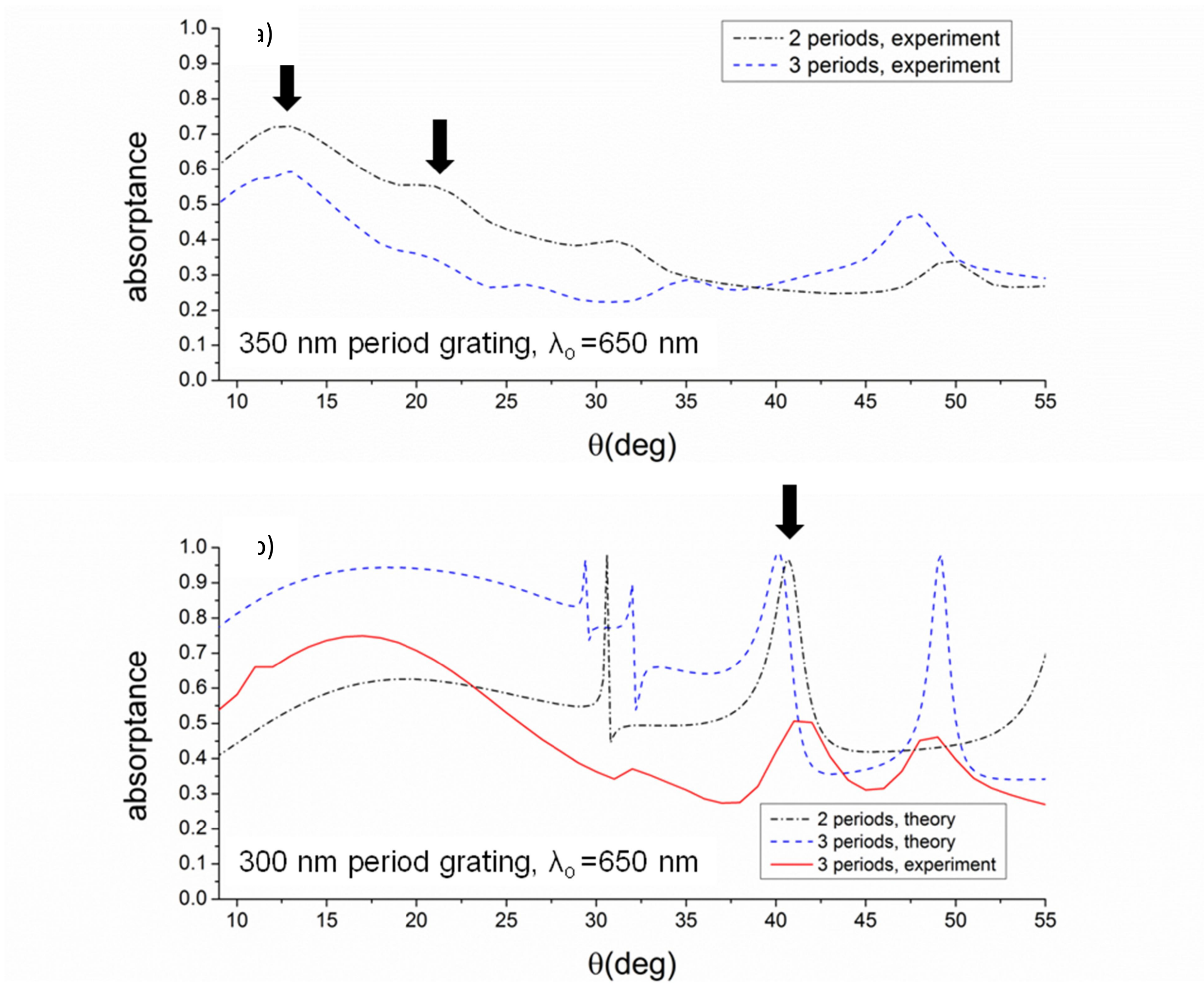


Figure 5. Measured and calculated absorptances as functions of θ of two- and three-periods thick photonic crystals backed by a gold grating with a period of (a) 350 nm and (b) 300 nm, when λ_o = 650 nm. Vertical black arrows identify the peaks that represent the excitaiton of SPP-wave modes.

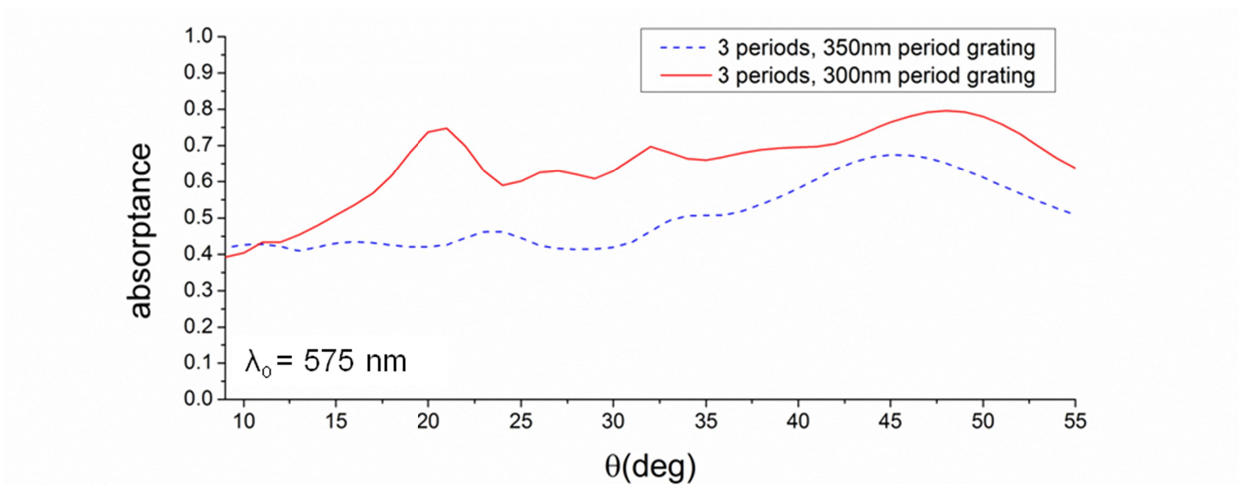


Figure 6. Measured absorptance A_p as a function of the angle of incidence θ of a three-period-thick photonic crystal backed by a gold grating with a period of either ~300 nm or ~350 nm, when λ_o = 575 nm.

Figure 6 shows the plot of measured absorptance A_p in relation to the angle of incidence θ for a three-period thick photonic crystal backed by a grating with a period of either 350 nm or 300 nm, when λ_o = 575 nm. Multiple peaks show that multiple guided modes (either SPP or waveguide) were excited in both samples. However, the grating with the smaller period leads to greater absorptance at shorter wavelengths.

No absorptance peaks are observed at infrared wavelengths when the grating period is smaller (Figure 4), but absorptance peaks appear at shorter wavelengths (Figures 5 and 6). The grating with the larger period (350 nm) exhibits more absorptance peaks at the same wavelengths. This shows that the decrease in the period of the grating shifts the SPP-wave modes to shorter wavelengths; however, the decrease in the period also results in higher efficiency of excitation.

4. CONCLUDING REMARKS

One-dimensional photonic crystals backed by gold gratings of different periods were used to study the effect of the period of the grating on the excitation of *p*-polarized SPP-wave modes. Multiple SPP-wave modes with distinct characteristics were excited using two different gratings; however, the grating with the smaller period supports multiple SPP-wave modes that are shifted to smaller wavelengths relative to the grating with the larger period. Multiple SPP-wave modes are expected to provide a route to enhance the efficiency of photovoltaics if incorporated into a thin-film solar cell or planar concentrator system.

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