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A Hybrid Phononic Waveguide Using Multilayer Structure at Mid-Infrared

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ABSTRACT

Surface phonon polaritons, SPhPs, result from the coupling or interaction of light with a phonon resonance. There has been extensive research into utilizing surface plasmon polaritons, SPPs, for subwavelength confinement of propagating waveguide modes for photonic integrated circuits. This work investigates the use of a multilayer system or insulator-metal-insulator (IMI) heterostructure as a SPhP-enhanced infrared waveguide where the metal response is due to phonons in a polar dielectric's Reststrahlen band. In addition, an IMI heterostructure supports types of modes: an even mode and odd mode that have their own unique trade-offs. For the odd mode as the metal film thickness decreases the confinement of the SPhPs decreases, and thus resulting in an increase in the SPhPs propagation length. Conversely, the even mode shows the opposite behavior with decreasing metal film where the confinement increases as propagation length decreases. This endeavor investigates the trade-off between the even and odd IMI modes, and the characterization of propagation length and model confinement, as applied to a hybrid phononic waveguide.

Keywords: Surface phonon polariton, insulator-metal-insulator, hybrid phononic waveguide, photonic integrated circuits

1. INTRODUCTION

The field of nanophotonics, the study of the manipulation of light on the nanoscale, has been used to develop fast and ultra-compact optical devices for integrated photonic circuits and sensing applications[1-3]. Polaritons result from the strong coupling between light and matter which results in anti-crossing, or level repulsive, dispersion curves[4]. Surface plasmon polaritons (SPPs) are excited on a metal-dielectric interface where the coupling is between the surface plasmon (electron oscillations) and incident light typical in the frequency ranges between the near infrared to ultraviolet. Hybrid plasmonic waveguiding structures results from the coupling of sub-diffractional plasmon polaritons with a mode in a dielectric waveguide[5]. However, in mid to long infrared applications plasmon polaritonic effects in noble metals are negligible. In this region of the spectrum, polar dielectrics like silicon carbide (SiC), silicon dioxide (SiO_2), and aluminum nitride (AlN) can support polaritonic effects via lattice vibrations, or phonons, in their crystalline structure[6,7]. The surface phonon polaritons, as they are called, are limited to a band of frequencies between transverse and longitudinal optical phonon resonances known as the Reststrahlen band[7]. The dispersion relation for SPhPs on a single interface between a polar dielectric and dielectric is given by[5,8,9]:

$$k_{sp} = k_0\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}, \tag{1}$$

where ε_m and ε_d are the complex permittivities of the polar dielectric and dielectric, respectively. From eq. 1, the propagation distance or length can be defined as[10]:

$$L_m = \frac{1}{2Im\{k_{sp}\}}. \tag{2}$$

Other hybrid geometries using thin films of noble metals have been reported[11]. Thin film plasmon polaritons fall into two broad arrangements including metal/insulator/metal (MIM) and insulator/metal/insulator (IMI) heterostructures. Here, the latter will be investigated in a hybrid geometry. It has been shown that the resulting IMI polaritons result in a pair of coupled surface polariton modes: even (asymmetric) and odd (symmetric) modes where the odd mode has been shown to have negative dispersion for thin metals[9,12]. Effective index for the odd and even SPhP modes for a thin film of

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AlN, complex dielectric permittivity seen in Figure 1.a, can be seen in Figure 1.c for a film thickness of 1.0 µm and 0.25 µm. The even and odd modes are referred to as short (SRSP) and long-range surface polaritons (LRSP), respectively, where the name is evident from the propagation lengths shown in Figure 1.d. The hybrid waveguide geometry shown in Figure 1.b will be explored for both SRSP and LRSP modes. The hybrid geometry is made up of a high index tracer suspended above a thin film of AlN of thickness t. To study the mode confinement and propagation length of the hybrid mode both the diameter, d, and suspension height, h, will be varied for both a case of SRSP and LRSP. The mode confinement is characterized by the mode area, defined as follows:

$$A_m = \frac{W_m}{\max\{W(\boldsymbol{r})\}} = \frac{\iint W(\boldsymbol{r})dxdy}{\max\{W(\boldsymbol{r})\}} \tag{3}$$

where W_m is the electromagnetic energy and W(**r**) is the energy density:

$$W(\boldsymbol{r}) = \frac{1}{2}\left[\frac{d(\varepsilon(\omega)\omega)}{d\omega}|E(\boldsymbol{r})|^2 + \mu_0|H(\boldsymbol{r})|^2\right]. \tag{4}$$

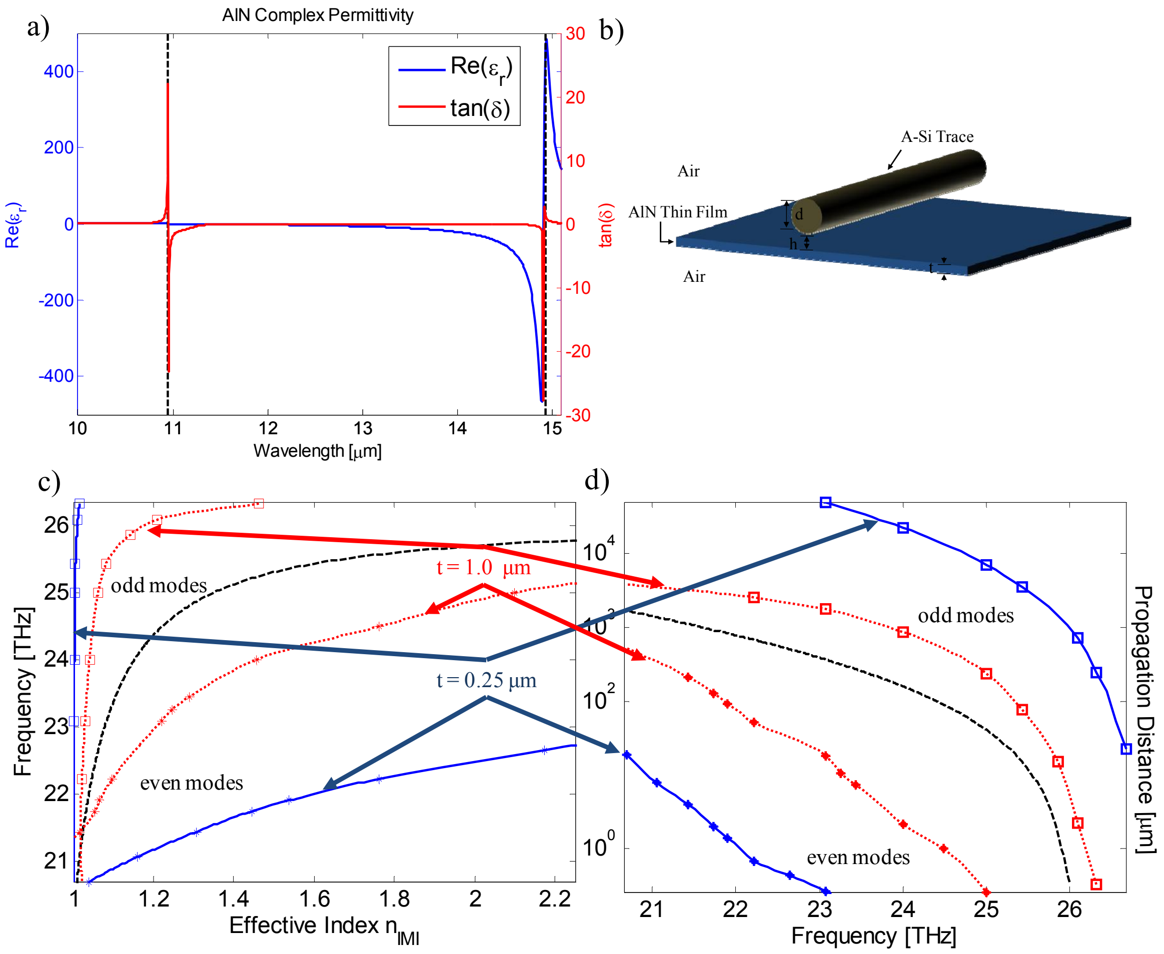

Figure 1. a) The real part of the complex permittivity and dielectric loss tangent of the AlN thin film layer are shown. The Reststrahlen band between the longitudinal (LO) and transverse optical (TO) phonon resonances is shaded. b) The hybrid geometry with a dielectric tracer of amorphous silicon, $\varepsilon_{A\text{-}Si}$= 7.457, with diameter d is suspended a distance h above a thin film of AlN with complex dielectric permittivity seen in part a. The thickness of the AlN thin film is t and the hybrid geometry is surrounded by air. The long (odd) and short-range (even) surface phonon polaritons' effective index (c) and propagation distance (d) for a AlN thin film multilayer structure of thickness of 1.0 and 0.25µm are shown. The analytical effective index and propagation distance from eq. 1 and 2, respectively, for a single AlN-air interface is shown by the black dashed lines in (c) and (d).

2. RESULTS

2.1 SRSP (even mode) hybrid phonon polariton waveguide

The even or SRSP mode will be considered for hybridization where the AlN thickness is 250 nm at wavelength of 13.5 µm. It can be seen from Figure 1.d that the SRSP's propagation length is approximately 1.0 µm, and this is reflected in the hybrid mode's propagation length in Figure 2.b. Figure 2.a shows the modal area that is normalized by the diffraction-limited area in free space, $A_0 = \lambda_0^2/4$, for the even hybrid mode, and the energy density of the hybrid mode is shown in Figure 2.c-f. Figure 3 shows the effective hybrid index in (a) and the phase and group velocities in (b). It can be seen in Figure 3.b that the even hybrid mode provides slow waves.

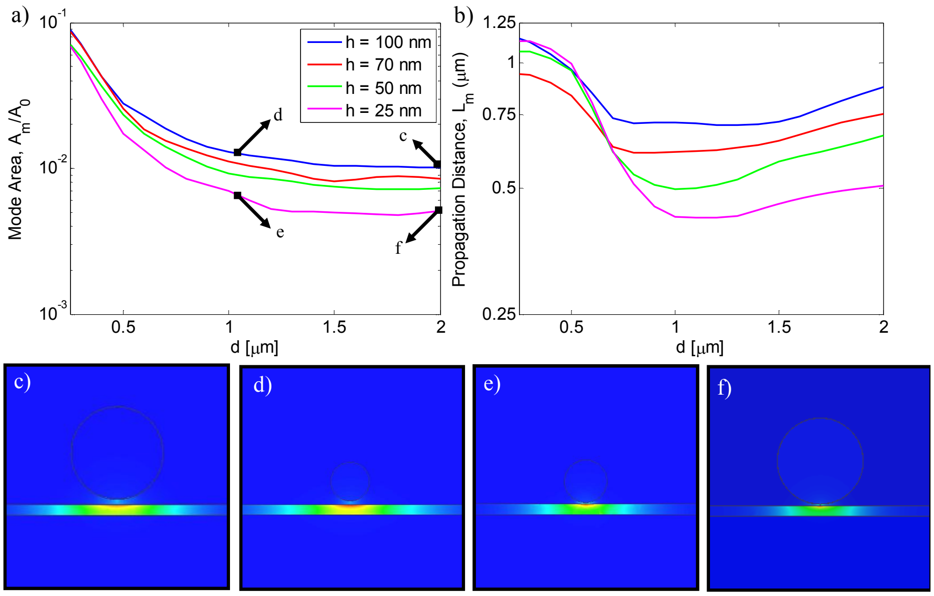

Figure 2. Modal area (a), A_m/A_0, and propagation distance (b) is shown as a function of diameter, d, for varies heights, h, at a wavelength of 13.5 µm for the even or SRSP mode. The energy density for [d, h] = [2.0, 0.10] µm (c), [d, h] = [1.0, 0.10] µm (d), [d, h] = [1.0, 0.025] µm (e), and [d, h] = [2.0, 0.025] µm (f).

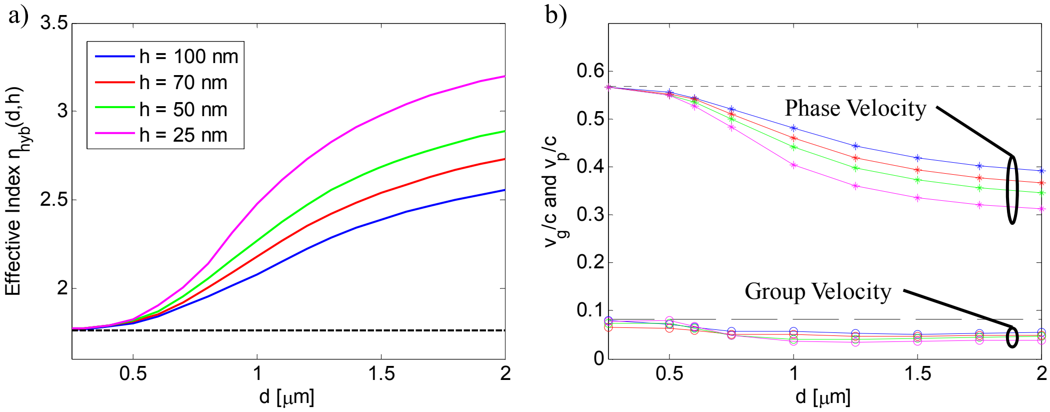

Figure 3. a) The effective hybrid index at a wavelength of 13.5 µm for the short range hybrid mode at various diameters and heights. b) The normalized phase and group velocities for the short range hybrid mode.

2.2 LRSP (odd mode) hybrid phonon polariton waveguide

The dielectric cylinder tracer will be next hybridized with the odd mode or LRSP with the AlN layer thickness of 1.0 µm and at a wavelength of 12.5 µm. The long range hybrid modes dispersion for h = 100 nm and d = [5.0, 4.0, 3.0, 1.0] µm can be seen in Figure 4. Linear dispersion curves are the cylinder modes at various d values. The blue dashed line is the LRSP dispersion that is also shown in Figure 1.c. Coupled mode theory (CMT)[13,14] and plasmonic hybridization[15] has been employed to describe the resulting hybrid mode in reference[5]. In conventional CMT, the mode splits into symmetric (lower) and anti-symmetric (upper) modes similar to the hybridization in the case of multilayer surface polariton geometry. It can be seen in Figure 4 that the hybrid dispersion is in-between the LRSP and the cylinder tracer dispersion unlike reported in conventional hybrid waveguide[11,16].

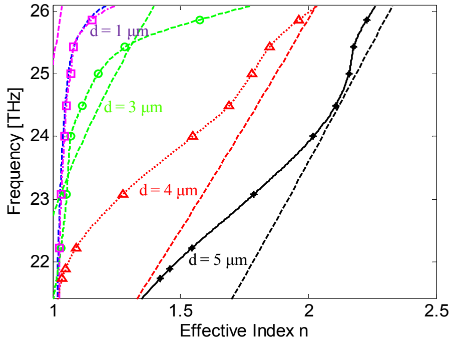

Figure 4. Dispersion relations for long range hybrid mode for h = 100 nm and d = [5.0, 4.0, 3.0, 1.0] µm shown by markers. The linear color dashed lines are the cylinder mode dispersion. The blue dash line is the AlN LRSP mode for t = 1.0 µm shown in Figure 1.c.

Similar to the even mode case, the propagation length and normalized mode area will be characterized as a function of diameter of the dielectric trace and height as shown in Figure 5.a and 5.b. Figure 5.c-f shows energy densities at the points indicated on the Figure 5.a plot. The effective hybrid index and normalized phase and group velocities are shown in Figure 6.a and 6.b respectively.

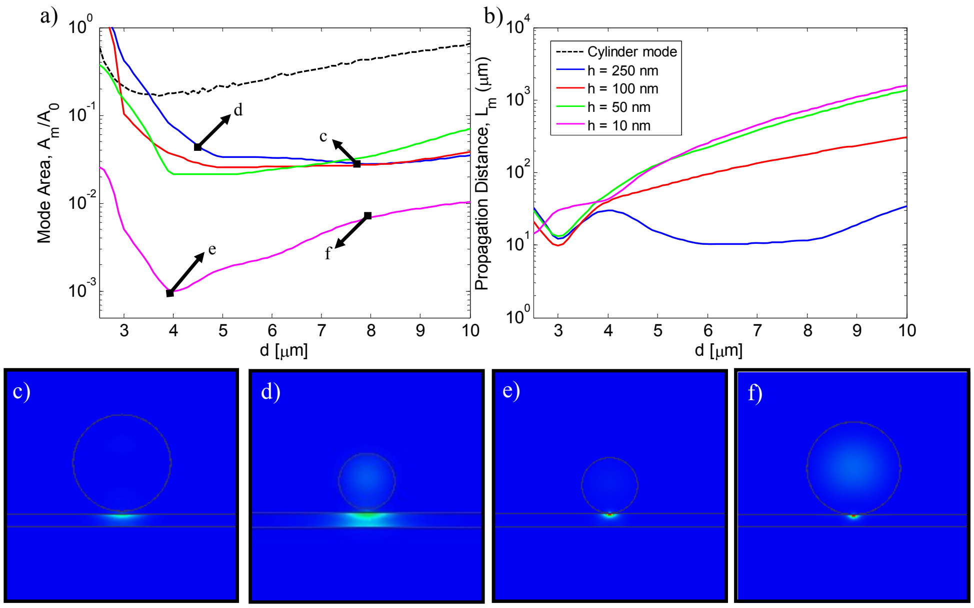

Figure 5. Modal area (a), A_m/A_0, and propagation distance (b) is shown as a function of diameter, d, for various heights, h, at a wavelength of 12.5 µm for the odd or LRSP mode. The energy density for [d, h] = [8.0, 0.25] µm (c), [d, h] = [4.0, 0.25] µm (d), [d, h] = [4.0, 0.01] µm (e), and [d, h] = [8.0, 0.01] µm (f). The cylinder mode A_m/A_0 is shown as a black dashed line in (a)

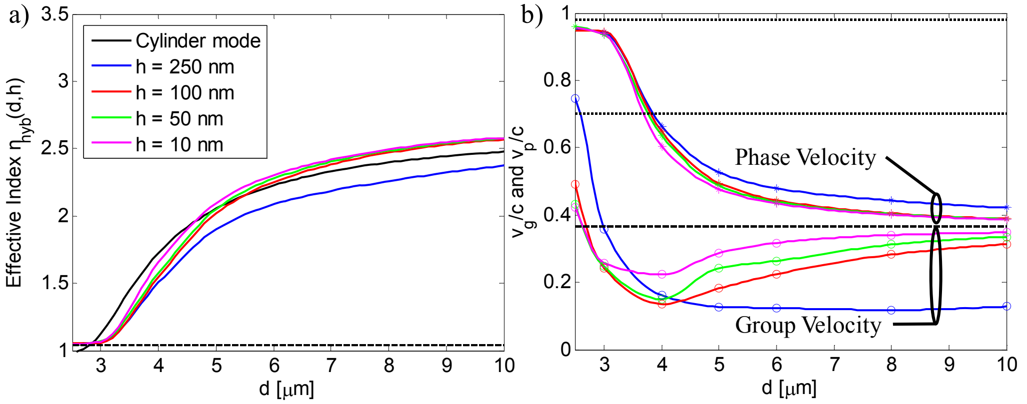

Figure 6. a) The effective hybrid index at a wavelength of 12.5 μm for the long range hybrid mode at various diameters and heights. b) The normalized phase and group velocities for the long range hybrid mode.

3. CONCLUSION

In conclusion, both cases of short and long range hybrid surface phonon polaritons have been characterized in terms of propagation distance, mode area, effective index, and phase/group velocities. It has been shown that although the even mode or short range hybrid mode has limited propagation lengths, the group velocity indicates slow wave propagation that is suitable of application in waveguide sensing[17]. On the other hand, the long range hybrid provides long propagation length that could potentially provide hundreds of microns to millimeters of propagation length in the mid to long infrared.

REFERENCES

[1] Fang, Y. and Sun, M., "Nanoplasmonic waveguides: towards applications in integrated nanophotonic circuits," Light: Science & Applications 4(e294), 1-11 (2015).

[2] Kirchain, R. and Kimerling, L., "A roadmap for nanophotonics," Nature Photonics 1(6), 303-305 (2007).

[3] Sorger, V. J., Oulton, R. F., Ma, R., and Zhang, X., "Toward integrated plasmonic circuits," Materials Research Society Bulletin 37(8), 728-738 (2012).

[4] Novotny, L., "Strong coupling, energy splitting, and level crossings: A classical perspective," American Journal of Physics 78(11), 1199-1202 (2010).

[5] Oulton, R. F., Sorger, V. J., Genov, D. A., Pile, D. F. P., and Zhang, X., "A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation," Nature Photonics 2(8), 496-500 (2008).

[6] Caldwell, J. D., et al., "Low-loss, extreme subdiffraction photon confinement via silicon carbide localized surface phonon polariton resonators," Nano Letters 13(8), 3690-3697, (2013).

[7] Caldwell, J. D., et al., "Low-loss, infrared and terahertz nanophotonics using surface phonon polaritons," Nanophotonics 4(1), 44-48, (2015).

[8] Yang, X., Liu, Y., Oulton, R. F, Yin, X.and Zhang, X., "Optical Forces in Hybrid Plasmonic Waveguides," Nano Letter 11(2), 321-328, (2011).

[9] Maier, S. A., [Plasmonics: Fundamentals and Applications], Springer, New York, (2007).

[10] Hsu, H. P., "On the general relation between α and Q (correspondance)," IEEE Transactions Microwave Theory Techniques 11(4), 258 (1963).

[11] Chen, L., Zhang, T., Li, X., and Huang, W., "Novel hybrid plasmonic waveguide consisting of two identical dielectric nanowires symmetrically placed on each side of a thin metal film," Optics Express 20(18), 20535-20544 (2012).

[12] Liu, Y., et al., "Negative group velocity of surface plasmons on thin metallic films," in Proc. SPIE 6323, Plasmonics: Metallic Nanostructures and their Optical Properties IV, 63231M (2006).

[13] Haus, H. A., [Waves and Fields in Optoelectronics], Prentice-Hall, Inc., Englewood Cliffs, NJ, (1984).

[14] Haus, H. A. and Huang, W., "Coupled-Mode Theory," Proceeding of the IEEE, 79(10), 1505-1518 (1991).

[15] Prodan, E., Radloff, C., Halas, N. J., and Nordlander, P. A., "Hybridization model for the plasmon response of complex nanostructures," Science 302(5644), 419-422 (2003).

[16] Sun, S., Chen, H.-T., Zheng, W.-J., and Guo, G.-Y., "Dispersion relation, propagation length and mode conversion of surface plasmon polaritons in silver double-nanowire systems," Optics Express 21(12), 14591-14605 (2013).

[17] Stievater, T. H., et al., "Low-loss suspended guantum well waveguides," Optics Express 16(4), 2621-2627 (2008).