Hybrid plasmonic waveguide for low-loss lightwave guiding

Jin Tae Kim,[1,2]* Jung Jin Ju,[1] Suntak Park,[1] Min-su Kim,[1] Seung Koo Park,[1] and Sang-Yung Shin[2]

[1] *Convergence Components and Materials Research Laboratory, ETRI, Daejeon 305-700, Republic of Korea*
[2] *Department of Electrical Engineering, KAIST, Daejeon 305-701, Republic of Korea*
**jintae@etri.re.kr*

Abstract: A hybrid plasmonic waveguide structure is proposed and fabricated for low-loss lightwave guiding along a metal stripe core. By embedding Au stripe in dual slab waveguides with high refractive-index contrast, the field of the guided mode is confined more in the two dielectric core layers. Thus, the propagation loss is significantly reduced. The guided mode is like a combination of a fundamental long-range surface plasmon polariton strip mode and a dual symmetric dielectric slab mode. We fabricate 5 nm-thick Au stripe optical waveguides and measure the optical properties at a wavelength of 1.31 µm. The propagation loss is less than 1.0 dB/cm with the metal stripe width of 1–5 µm.

OCIS codes: (230.7370) Waveguides; (240.6680) Surface plasmons; (130.3120) Integrated optics devices.

References and links

1. D. Sarid, "Long-range surface-plasma waves on very thin metal films," Phys. Rev. Lett. **47**(26), 1927–1930 (1981).
2. P. Berini, "Plasmon-polariton waves guided by thin lossy metal films of finite width: Bound modes of symmetric structures," Phys. Rev. B **61**(15), 10484–10503 (2000).
3. T. Nikolajsen, K. Leosson, and S. I. Bozhevolnyi, "Surface plasmon polariton based modulators and switches operating at telecom wavelengths," Appl. Phys. Lett. **85**(24), 5833–5835 (2004).
4. R. Charbonneau, N. Lahoud, G. Mattiussi, and P. Berini, "Demonstration of integrated optics elements based on long-ranging surface plasmon polaritons," Opt. Express **13**(3), 977–984 (2005).
5. S. Jetté-Charbonneau, R. Charbonneau, N. Lahoud, G. Mattiussi, and P. Berini, "Demonstration of Bragg gratings based on long-ranging surface plasmon polariton waveguides," Opt. Express **13**(12), 4674–4682 (2005).
6. J. T. Kim, J. J. Ju, S. Park, M. S. Kim, S. K. Park, and M.-H. Lee, "Chip-to-chip optical interconnect using gold long-range surface plasmon polariton waveguides," Opt. Express **16**(17), 13133–13138 (2008).
7. P. Berini, R. Charbonneau, N. Lahoud, and G. Mattiussi, "Characterization of long-range surface-plasmon-polarition waveguides," J. Appl. Phys. **98**(4), 043109 (2005).
8. J. T. Kim, S. Park, J. J. Ju, S. K. Park, M.-S. Kim, and M. H. Lee, "Low-loss polymer-based long-range surface plasmon-polariton waveguide," IEEE Photon. Technol. Lett. **19**(18), 1374–1376 (2007).
9. S. Park, J. J. Ju, J. T. Kim, M. S. Kim, S. K. Park, J.-M. Lee, W.-J. Lee, and M.-H. Lee, "Sub-dB/cm propagation loss in silver stripe waveguides," Opt. Express **17**(2), 697–702 (2009).
10. J. T. Kim, J. J. Ju, S. Park, S. K. Park, M.- Kim, J.-M. Lee, J.-S. Choe, M.-H. Lee, and S.-Y. Shin, "Silver stripe optical waveguide for chip-to-chip optical interconnection," IEEE Photon. Technol. Lett. **21**(13), 902–904 (2009).
11. J. T. Kim, S. Park, S. K. Park, M.- Kim, M.-H. Lee, and J. J. Ju, "Gold stripe optical waveguides fabricated by a novel double-layered liftoff process," ETRI J. **31**(6), 778–783 (2009).
12. J. Guo, and R. Adato, "Extended long range plasmon waves in finite thickness metal film and layered dielectric materials," Opt. Express **14**(25), 12409–12418 (2006).
13. R. Adato, and J. Guo, "Modification of dispersion, localization, and attenuation of thin metal stripe symmetric surface plasmon-plariton modes by thin dielectric layers," J. Appl. Phys. **105**(3), 034306 (2009).
14. FIMMWAVE Version, 4.6, a vectorial waveguide solver. Photon Design, 2006.
15. C. Reale, "Optical constants of vacuum deposited thin metal films in the near infrared," Infrared Phys. **10**(3), 173–181 (1970).

1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves that propagate along a metal-dielectric interface. For a thin metal film of infinite width embedded in a homogeneous

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dielectric, the SPP modes were excited at the upper and lower interfaces. They couple and form a lossy asymmetric mode and a low loss symmetric mode, i.e. long-range SPP (LRSPP) mode [1]. When the metal film becomes a stripe by reducing its width, the lateral confinement of the LRSPP is possible and the LRSPP strip mode is formed [2]. The LRSPP strip mode is excited directly by end-fire coupling and the field distribution can be adjusted to that of a single-mode fiber by varying the stripe width and thickness. This attractive fact promotes their application in integrated optical devices and optical interconnections [3–6].

The LRSPP waveguide holds potential for the development of novel optical interconnection technique. However, comparatively high propagation loss limits its application. For practical application, the propagation loss of the LRSPP waveguide should be reduced to that of the dielectric waveguide. There have been many efforts to reduce the propagation loss of the LRSPP waveguide by minimizing the metal thickness and width, lowering the refractive index of the clad material, and optimizing the fabrication process to obtain good quality of metal stripes [7–11]. Instead of gold, silver is preferable because silver is less absorbent than gold at the wavelength of telecommunication [7,9,10]. By placing thin intermediate dielectric layers with low refractive index below and above the metal film, the propagation loss could be reduced [12,13]. Though those methods are effective, the intensity of the guided mode supported by the metal stripes is always maximum at the metal-dielectric interface so that the ohmic loss of the metal is inevitable. Thus, it is difficult to reduce the propagation loss of the LRSPP waveguide to that of the dielectric waveguide.

In this paper, we propose a new plasmonic waveguide structure utilizing multilayered dielectric cladding to lower the propagation loss of metal stripe optical waveguides. To reduce the field intensity at the metal-dielectric interfaces, we place two dielectric slab waveguides with high refractive-index contrast at the upper and lower parts of the metal stripe. We made a theoretical investigation on the properties of guided mode in the proposed hybrid plasmonic waveguide structure. We fabricated 5 nm-thick Au stripe with the suggested cladding structure and measured the optical characteristics. The experimental results are compared with theoretical predictions.

2. Architectural concepts and theoretical analysis

The field intensity of the long-range surface plasmon mode is maximum at the metal-dielectric interface. To lower the propagation loss of the LRSPP waveguide, the field intensity at the metal-dielectric interface should be reduced. For this purpose, dielectric slab waveguides with high refractive-index contrast are placed on the upper and lower sides of the metal stripe, as shown in Fig. 1. The metal stripe is embedded in a low index cladding of thickness h. The thickness of the core is d. The refractive index of the inner-cladding (n_1) is lower than that of the core (n_2). The refractive index of the outer-cladding (n_3) is the same as that of the inner-cladding layer.

The guided modes of 5 nm-thick Au stripes embedded between dual slab waveguides with high-refractive index-contrast are derived by the finite element method (FEM), using a commercial package [14]. The complex refractive index of Au was $0.4081–8.305i$ at a wavelength of 1.31 μm. The refractive indices of the cladding (n_1 and n_3) and core (n_2) are 1.514 and 1.524, respectively. The thickness of the core layer and the outer-cladding layer is 5 μm and 20 μm, respectively. Since the transverse-magnetic (TM) modes are guided along a metal strip with low attenuation, TM-like modes are considered. The guided mode propagates along the z direction.

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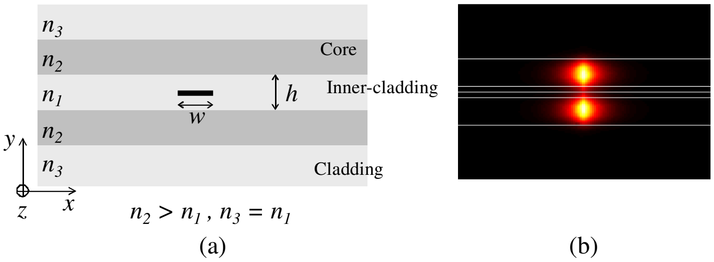

Fig. 1. Cross-sectional view of the hybrid plasmonic waveguide and calculated guided mode. (a)A thin metal stripe is embedded between dual slab waveguide with high refractive-index contrast and (b) calculated guided mode.

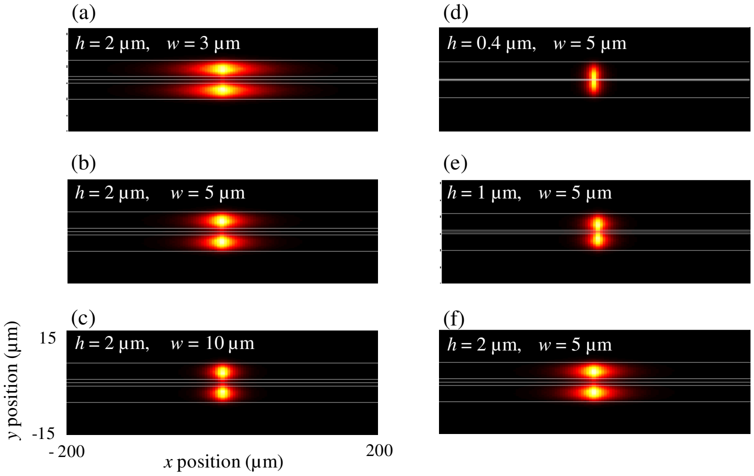

Fig. 2. Calculated guided mode of the proposed hybrid plasmonic waveguide as a function of (a)–(c) metal stripe width w, (d)–(f) inner-cladding thickness h.

Without the metal stripe, the waveguide structure is considered as a dual core slab waveguide with high refractive-index contrast. If the distance h between the two cores is sufficiently large, each slab waveguide supports the fundamental mode in the high refractive index region. If the distance h is small enough for light to couple from one core waveguide to the other, the whole structure of core layers must be analyzed to get the even and odd symmetric super-modes. The even symmetric slab mode is confined in the vertical direction. However, the mode is not confined in the lateral direction because of infinite core width. The lateral confinement of mode is possible by embedding a metal stripe in the inner-cladding layer, as shown in Fig. 1. The even symmetric hybrid mode in this structure is like a combination of the symmetric LRSPP strip mode and a dual symmetric dielectric slab mode.

The inner-cladding thickness and the metal stripe width have a great effect on the lateral confinement of the hybrid mode. Figure 2(a), 2(b), and 2(c) exhibit the guided mode with the variation of the metal width. The inner-cladding thickness is 2 µm. As the metal width w becomes wider, the lateral mode size in the two core layers decreases. It is like the LRSPP strip mode that is tightly bound to thick and wide metal stripe. For a metal stripe wider than 10 µm, the lateral mode size of the core layer is slightly larger than the metal width. When the metal width is larger than 30 µm, it supports hybrid multi-modes. The dependence of the lateral confinement on the inner-cladding thickness is shown in Fig. 2(d), 2(e), and 2(f). The metal stripe width is 5 µm. As the inner-cladding thickness increases, the hybrid mode is separated in the vertical direction more and the lateral mode size of the core layer increases. It means that the field of the guided mode is confined more in the two dielectric core layers.

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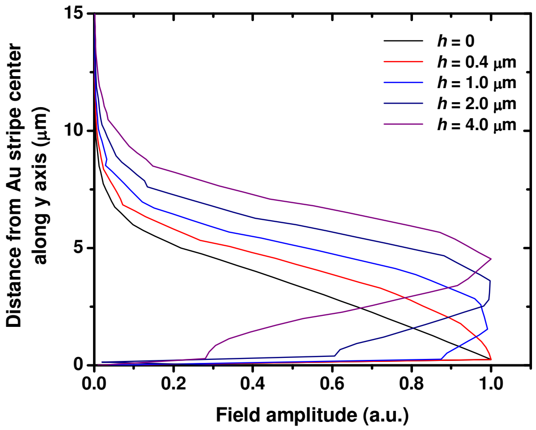

Fig. 3. E_y field profiles of the hybrid plasmonic waveguide with the variation of the inner-cladding thickness h.

Generation of a hybrid mode is clearly demonstrated in the E_y field profile, as shown in Fig. 3. It exhibits the E_y field profiles in the vertical direction of Au stripes with 5 µm width and 5 nm thickness as we change the inner-cladding thickness h. Without the inner-cladding layer, the LRSPP strip mode is excited in the core layer. The magnitude of E_y field is maximum at the metal-dielectric interfaces and decays rapidly. In the presence of the inner-cladding layer, the E_y field amplitude at the center of the core layer increases gradually. This means that the excitation of the dielectric slab mode begins. As the inner-cladding thickness h increases further, the E_y field amplitude of the slab increases larger than that of the LRSPP strip. The field intensity of the guided mode is confined mostly in the core layers rather than the metal stripe. In the lateral direction, the field is still confined by a metal stripe. Thus, the hybrid mode propagates along the metal stripe. When the inner-cladding thickness is very large, the light confinement by the metal stripe disappears and the mode is transformed to a symmetric dielectric slab mode.

Without the inner cladding layer ($h = 0$), the mode field is more confined to the metal by the low refractive index outer-cladding layer. Therefore, the propagation loss is higher than that of the metal stripes embedded in a single dielectric layer. However, the inner-cladding layer with low refractive index makes the mode field of the guided mode be confined more in the two core layers. The magnitude of the field at the metal-dielectric interface decreases and, consequently, low loss propagation of the mode is expected.

The calculated propagation loss of hybrid plasmonic waveguide depending on the metal width and the inner-cladding thickness is shown in Fig. 4. The propagation length is defined by the length that power is attenuated by e^{-1}, i.e. $L = 1/(2 \times Im\beta)$. The dielectric materials are assumed as lossless. For comparison, the propagation loss of Au stripe embedded in a single dielectric layer is plotted in the figure. When the inner-cladding is absent ($h = 0$), the propagation loss of the LRSPP strip mode is higher than that of the metal stripes embedded in a single dielectric layer. On the other hand, the propagation loss of the metal stripe embedded between dual slab waveguide is significantly reduced as the inner-cladding thickness h increases. This is attributed to the fact that the intensity of the guided mode is high in the core layers. The symmetric LRSPP strip mode is bound less to the metal stripe as the stripe width and the thickness decrease [2]. Therefore, the propagation loss of the suggested hybrid plasmonic waveguide decreases as the metal width decreases.

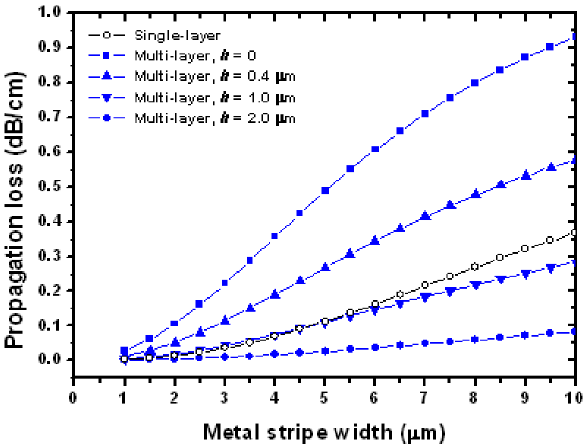

Fig. 4. Calculated propagation loss of the hybrid plasmonic waveguide depending on the inner-cladding thickness and the metal stripe width.

3. Experimental results and discussions

In order to confirm the theoretical results, we fabricated the proposed hybrid plasmonic waveguide. First, the outer-cladding layer was formed to be 20 μm by spin-coating and UV curing. Consequently, the core layer is 5 μm and the inner-cladding is 1 μm. Then, Au stripes with different widths were evaporated thermally on the pre-patterned AZ 5206E photo-resist. The inner-cladding, core layer, and outer-cladding were formed on Au stripes with 5 μm thickness were 1, 5, and 20 μm, respectively. We used a commercial UV-curable polymer, FOWG (ChemOptics), for fabricating dielectric multilayer. The refractive indices of the cladding and core layer are 1.514 and 1.524, respectively. For comparison, Au LRSPP waveguides in a single polymer were separately fabricated with the same polymer material. The optical characteristics of the fabricated hybrid plasmonic waveguides were measured at a wavelength of 1.3 μm by using a single-mode polarization-maintaining fiber.

Figure 5 shows the measured propagation and coupling loss of the fabricated hybrid plasmonic waveguides. Without the inner-cladding layer (h = 0), the propagation loss is higher than that of the LRSPP waveguide with single dielectric layer because the finite core layer thickness make the LRSPP strip mode be bound more tight to the metal stripe. However, the measured propagation loss of the hybrid plasmonic waveguide with the inner-cladding is significantly reduced as the theory predicted. It decreases as the metal width decreases. The propagation loss is less than 1.0 dB/cm for Au stripes of width smaller than 5.0 μm. The lowest propagation loss of 0.25 dB/cm was achieved with a 2.5 μm-wide stripe.

The measured propagation loss is about one order of magnitude larger than the theoretical prediction. This is mainly due to the metal film imperfection. When the evaporated metal film is extremely thin, the density of the metal film decreases [15]. Reduction of the metal film density leads the inhomogeneities in the gold structure, and could be a part of the increment of the propagating loss. In addition, the generation of sharp pin-like and shark-fin-like structures on the edge of the metal stripes may increase the propagation loss because those structures scatter the field of the surface plasmons. The fabrication of Au stripe with proper square cross-sections without the parasitic structures could reduce the propagation loss further [11].

Though the propagation loss is significantly reduced, the coupling loss goes up noticeably as Au stripe width decreases. The increased coupling loss may be attributed to the increase of the lateral mode size in the core layer. The lateral mode size is very sensitive to the variation of the metal stripe width. The lateral mode size increases as the metal stripe width decreases because a narrower metal stripe confines the light less tightly. On the contrary, the vertical mode size of the guided mode changes very little because the thickness of the inner-cladding and core layer is fixed. This is clearly confirmed by the near-field images of the hybrid plasmonic waveguide that are captured by a CCD camera. Figure 6 shows the images. The scale bar in each figure indicates the metal stripe width. The lateral mode size increases as the metal stripe width decreases. On the other hand, the vertical size is nearly the same.

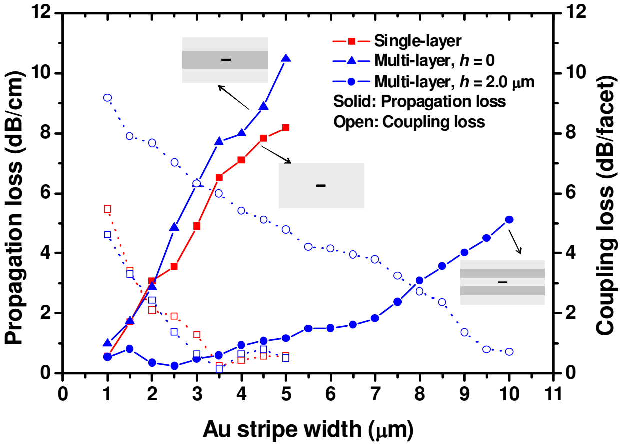

Fig. 5. Measured propagation and coupling losses of fabricated hybrid plasmonic waveguide.

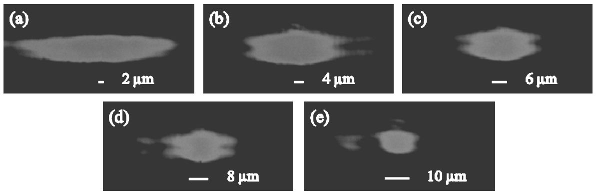

Fig. 6. Microscope images of the observed far-field guided mode of the hybrid plasmonic waveguide.

For commercial hand-held devices that may require optical interconnection, flexibility of the optical waveguide is highly required. The proposed hybrid plasmonic waveguide is made of flexible material. Since the dielectric multilayer confines the guided mode tightly in the vertical direction, very low vertical bending loss is also expected. Unsatisfactory coupling loss may be improved by placing the wide metal stripe with low coupling loss at the input and output ends. The suggested metal stripe optical waveguide structure is easily fabricated by simple spin-coating, UV-curing, and lift-off processes. Deep dry etching or imprinting process that increases the cost for fabricating the thick rectangular core is not required. If Cu is substituted for costly Au, the fabrication cost could be reduced more. Thus, the suggested hybrid plasmonic waveguide will be very effective for some optical interconnection.

4. Conclusion

In order to reduce the propagation loss of Au stripe optical waveguide, we proposed a new hybrid plasmonic waveguide structure. The metal stripe is embedded between the dual slab waveguides with high refractive-index contrast. The field of the guided mode is confined more in the dielectric core layers, and the propagation loss is significantly reduced as the metal stripe width decreases. The propagation loss of less than 1.0 dB/cm was obtained at a wavelength of 1.31 μm when the width of Au stripe is smaller than 5 μm. The suggested hybrid plasmonic waveguide will be effective for some optical interconnection.

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