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A review of crosstalk research for plasmonic waveguides

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Plasmonic waveguides, as a competitive candidate, have been widely studied in rapid developing photonic integrated circuits (PICs) and optical interconnection fields. However, crosstalk between plasmonic waveguides is a critical issue that has to be considered in practice. Actually, crosstalk dominates the ultimate integration density of the planar photonic circuits. This paper reviews the recent research work on evaluation methods and crosstalk suppression approaches of plasmonic waveguides. Three crosstalk evaluation methods based on comparison of specific parameters of waveguides have been summarized. Furthermore, four specific approaches to reduce crosstalk have been illustrated as two categories according to their impacts on waveguide performances and the whole circuit. One means of crosstalk suppression is changing the placement of waveguides, which could maintain the transmission characteristics of the original waveguide. The other means is inserting medium, which has the advantage of occupying smaller space compared to the first method. Consequently, to suppress crosstalk between plasmonic waveguides, one should choose suitable approach.

Keywords: crosstalk; surface plasmons; guided waves; photonic integrated circuits; optical interconnection

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Introduction

Surface Plasmon Polariton (SPP) can break the diffraction limitation and display a promising way to achieve photonic integrated circuits (PICs)[1,2]. It is widely believed that PICs based on SPP have great potential in the realization of optical interconnection information transmission technology[3,4]. Recently, various plasmonic waveguide schemes have been demonstrated, such as metallic nanosphere chain waveguides[5,6], metallic wire, stripe and slab waveguides[7,8], the dielectric loaded metal[9,10], channel plasmon polaritons[11,12], metal wedges[13,14], slot and gap waveguides[15–17], hybrid plasmonic waveguides[18–20], etc. In current study, these plasmonic waveguides have made a good compromise between the propagation length and the mode confinement, which is helpful for achieving efficient transmission of energy. In the design of PICs, in addition to considering the transmission characteristics of a single waveguide, the influence between waveguides must be examined and weighed. Generally, there will be a certain degree of coupling and crosstalk between two adjacent waveguides inevitably due to their modes overlap. More specifically, the closer the distance between the two waveguides are, the stronger the crosstalk between them will be, which weakens the effective transmission of energy in each single waveguide. Similarly, due to the strong mode confinement of waveguides, low crosstalk can be understood as that the mode overlap between two waveguides is much weaker and almost negligible. Furthermore, in order to avoid crosstalk between waveguides, a specific distance between the waveguides must be maintained, which in turn limits the density to a certain extent. Therefore, crosstalk is widely regarded as an indispensable parameter of packing density of optical waveguides and devices. It is essential to analyze crosstalk comprehensively and study the method of suppressing crosstalk for the practical applications of plasmonic waveguide in PICs.

Some groups have conducted crosstalk research. Zia R et al.[21] investigated the coupling between

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two-dimensional (2D) metal-dielectric-metal (MDM) plasmonic waveguides, and pointed out that such waveguides can be put at a distance of 150 nm without significant crosstalk. Liu L et al.[22] investigated the coupling between 3D plasmonic slot waveguides formed on the metal film, and indicated a larger coupling length means smaller crosstalk in the two waveguides. Veronis G et al.[23] proposed a method to assess crosstalk and an approach for suppressing crosstalk with the thin metal film. Bian Y et al.[24] pointed out that the crosstalk between adjacent waveguides instead of the physical dimensions of the waveguide dictates the ultimate integration density of the planar photonic circuits. Song Y et al.[25] numerically investigated hybrid plasmonic waveguides composed of a dielectric nanowire on a metal surface as well as crosstalk between such waveguides. Xiao J et al.[26] proposed a low crosstalk structure due to the existence of subwavelength mode constraints and the weak overlap between the two waveguides. Devaux E et al.[27] extrapolated a crosstalk evaluation method and clearly explained the effect of separation distance on crosstalk. Han Z et al.[28] enumerated different types of waveguides have different propagation losses, and put forward that it is more meaningful to compare the absolute values of coupling length with the propagation length of SPPs in a single plasmonic waveguide. Huang C C et al.[29] deemed that no coupling occurs between waveguides if the value of the ratio of coupling length to mean propagation length exceeds 10. Shruti et al.[30] showed that the field decays much slower in the dielectric compared to that of the metal, replacing the dielectric by metallic strip reduces the crosstalk. Chen L et al.[31] presented a graphene-based hybrid plasmonic waveguide with ultra-low crosstalk by analyzing the ratio of coupling length to propagation length. Ma A et al.[32] studied a classical surface plasmon polariton waveguide by the improved coupled mode theory, and presented a crosstalk evaluation method based on power comparison. Kuznetsov E V et al.[33] demonstrated the suppression of crosstalk between two dielectric nanowaveguides by placing an auxiliary linear waveguide between loaded waveguides spaced by one wavelength. He X et al.[34] proposed an ultralow loss graphene-based hybrid plasmonic waveguide with lower crosstalk, which is much better than those reported in hybrid plasmonic waveguides[31]. Moreover, there are other plasmonic waveguides based on crosstalk researches have been published[35–44].

In this paper, we review the recent research progress of crosstalk between plasmonic waveguides. Firstly, we introduced three methods for evaluating crosstalk based on the comparison of different parameters of waveguides. Then, according to the influence on waveguide performances and the entire circuit, we summarized four approaches of reducing crosstalk into two categories, including changing waveguide placement and inserting medium.

Theory of crosstalk evaluation

A method based on the ratio of coupling length to mean attenuation length

In the study of crosstalk between plasmonic slot waveguides, Veronis G et al.[23] proposed a crosstalk evaluation method based on the ratio of coupling length to mean attenuation length. In two adjacent waveguides system, the complex propagation constant is the basic parameter to calculate crosstalk. Here, $\beta_s+i\alpha_s$ and $\beta_a+i\alpha_a$ represent the complex propagation constants for the symmetric and anti-symmetric modes, respectively. The coupling length L_c is the length required for completely power transfer from one waveguide to the other, which is expressed as:

$$L_c=\frac{\pi}{\beta_s-\beta_a} \quad . \tag{1}$$

As is known to all, loss of energy exists in the transmission of plasmonic waveguide, such as Ohmic losses (the loss comes mainly from the metal absorption). In the system composed of two adjacent waveguides, the energy is transferred periodically between the two waveguides due to coupling and crosstalk, which further increases the loss. In each coupling period, there is a maximum in power coupled from one waveguide to the other, that is, the maximum transfer power P_{max}, which is expressed as:

$$P_{max}\cong\frac{\exp[-2\chi\arctan(1/\chi)]}{1+\chi^2},\ \chi=\frac{2L_c}{\pi L_p} \quad , \tag{2}$$

here, L_p is the mean attenuation length with $L_p = 2/(\alpha_s+\alpha_a)$. In the weak coupling regime, the mean attenuation length is approximately as twice as long of the propagation length.

For two plasmonic waveguides that transmit energy independently, the stronger the coupling between them is, the greater the crosstalk is. Typically, when coupling length exceeds the corresponding propagation length of the waveguide, the crosstalk of the coupling system can be deemed very small[31,45]. This method is suitable for crosstalk evaluation between waveguides with complex structures, such as the long-range air-hole assisted subwavelength waveguides proposed in Ref.[46]. From formulas (1) and (2), shorter coupling length L_c and greater maximum transfer power P_{max} (close to 1) indicate stronger crosstalk. If the value of L_c/L_p exceeds 10, P_{max} approaches zero, and it is deemed that no coupling occurs between waveguides[29]. Although reducing the average attenuation length can reduce the maximum transfer power, it also means the degradation of the waveguide's transmission performance, which is not allowed by the design. Therefore, to suppress crosstalk between plasmonic waveguides, we should increase the coupling length L_c and decrease the maximum transfer power P_{max} in the design.

A method based on the ratio of the electric field intensity in the adjacent waveguide to the one in the main waveguide

In exploring the coupling characteristics of the channel plasmon-polariton waveguides, Devaux E et al.[27] proposed a crosstalk evaluation method considering the electric field density. Unlike the former method, this method is mainly based on the ratio of the electric field intensity in the adjacent waveguide to the one in the main waveguide. According to theoretical derivation, when the coupling distance is equal to the coupling length L_c, the crosstalk reaches the maximum value. So, the maximum crosstalk XT_{max} can be calculated with formula (3).

$$XT_{max} = XT(L_c) = \{\tanh(\mathrm{Im}[\Delta n]k_0 L_c)\}^{-2} \ , \quad (3)$$

where Δn is the half-difference for the effective indexes of symmetric and anti-symmetric modes, and $\Delta n = (n_s - n_a)/2$. k_0 is the wave number in vacuum, which can be expressed as $k_0 = 2\pi/\lambda$. The coupling length L_c can be obtained with formula (1).

The unit of XT_{max} is dB. XT_{max} can be used to describe the intensity of crosstalk directly, and compare the crosstalk between different systems conveniently. In addition, the crosstalk intensity is mainly related to the coupling length and propagation length. When the coupling length is much longer than the propagation length, the system composed of two adjacent waveguides exhibits weak coupling and low crosstalk. With the aim to reduce the crosstalk between the waveguides while maintaining good transmission performance of the waveguide, we should keep the coupling length L_c as long as possible, and the value of maximum crosstalk XT_{max} as small as possible.

A method based on the ratio of the output power in the second waveguide to the input power in the first waveguide

By improving coupled mode theory, Ma A et al.[32] proposed a crosstalk evaluation method in wedge plasmon polariton waveguides. This method is based on the ratio of the output power in the second waveguide to the input power in the first waveguide. To simplify the model, they assume that the initial transmission optical power of the first waveguide P_0 is 1. The first waveguide couples periodically with the second waveguide along the propagation direction z-axis. Therefore, the crosstalk XT, which is a function of the propagation distance z, can be evaluated by the normalized power in the second waveguide. The crosstalk XT is expressed as following:

$$XT = P_2(z) = 10\lg P_2(z)/\mathrm{dB} \ , \quad (4)$$

here, $P_2(z)$ is the power distribution in the second waveguide along propagation direction z.

This crosstalk evaluation method is based on the comparison of optical power during the propagation of two waveguides, and can be widely used in the crosstalk analysis of plasmonic waveguides. Unlike the above two crosstalk evaluation methods, this method obtains the normalized crosstalk power at the given propagation distance. Meanwhile, only at a unified propagation distance, comparing the crosstalk between the two systems is meaningful. It is worth noting that this crosstalk evaluation method is based on the propagation distance. By using improved coupled mode theory, this method can better describe the crosstalk of a more complex multi-waveguide system. Obviously, the larger the power of the second waveguide is, the stronger the crosstalk is. By comparing the intensity of crosstalk in a particular propagation distance, we can design the lower crosstalk structure.

Approach of reducing crosstalk—changing waveguide placement

Increasing separation distance

Among the above-mentioned theory, increasing coupling length can reduce crosstalk effectively. In general, the common method of increasing coupling length is to increase the separation distance. Using the first crosstalk evaluation method, Ref.[23] studied the crosstalk of four structures, which are all formed on the same thin metal film, as shown in Fig. 1: (a) two coupled 2-D MDM plasmonic waveguides, (b) two coupled symmetric plasmonic slot waveguides, (c) two vertically-coupled symmetric plasmonic slot waveguides, and (d) two coupled asymmetric plasmonic slot waveguides. Simultaneously, they presented the relationship of coupling length and maximum transfer power of different plasmonic waveguides and the separation distance D in Figs. 1(e) and 1(f).

Using the second crosstalk evaluation method, Ref.[27]

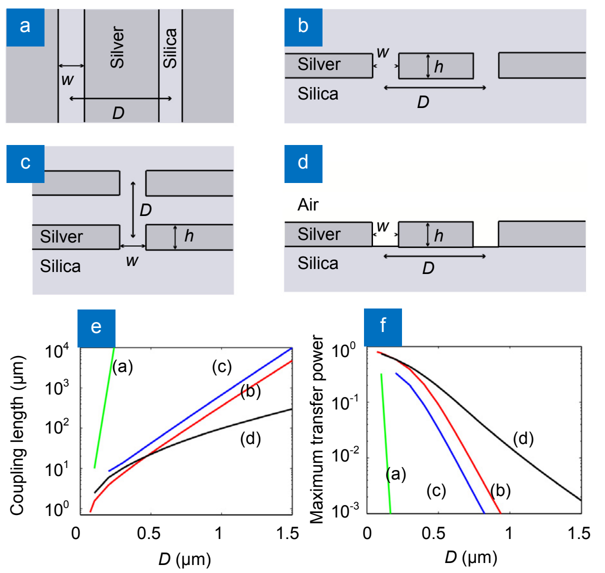

Fig. 1 | Four different waveguide schematics ((a), (b), (c), (d)) and the dependences of (e) coupling length L_c and (f) maximum transfer power P_{max} on separation distance D[23].

studies the directional coupler based on channel plasmon-polariton waveguides. Fig. 2 shows the schematic of the channel plasmon-polariton waveguides, and the crosstalk of this waveguides as a function of the separation distance *d* at different wavelengths and longitudinal coordinates *z*.

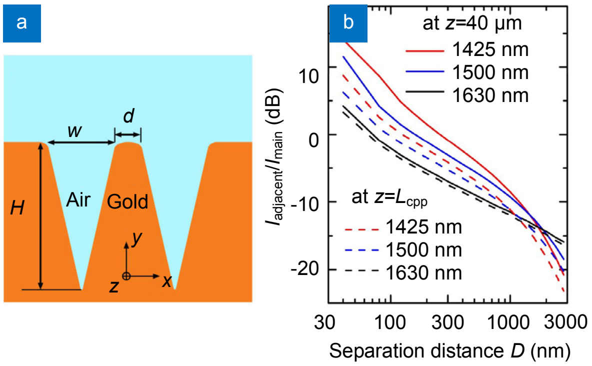

Fig. 2 | (**a**) The schematic of two adjacent parallel channel plasmon-polariton waveguides. (**b**) The crosstalk performance with specific parameters[27].

Using the third crosstalk evaluation method, Ref.[32] analyzed the normalized crosstalk power of wedge plasmon polariton (WPP) waveguides at different separation distances and waveguide lengths *L* with specific wedge height (Fig. 3).

All the three crosstalk evaluation methods imply that increasing the separation distance between plasmonic waveguides can effectively reduce crosstalk. The problem of this approach is that it needs more space in the overall design. In other words, this approach limits the density of the device integration to some extent. Usually, to make a tradeoff between small dimension and minimum crosstalk, the processing conditions of waveguide devices and the proximity effect of photolithography should be taken into account. More specifically, the separation distance of waveguides should not be too small, for example, for silicon nanowire waveguides, it should be more than 150 nm. The separation distance of plasmonic waveguides needs to be adjusted according to the actual situation.

Changing the relative position of hybrid waveguides

For the hybrid waveguide composed of multilayer materials, the crosstalk between adjacent waveguides can be reduced by changing the relative position of the overall waveguide structure. Figure 4(a) in Ref.[25] shows the conventional placement of hybrid waveguide, which is composed of three layers: silicon (Si), silica (SiO_2) and silver (Ag). Rotate the whole structure by 90 degrees, and the new positions of the two waveguides are shown in Fig. 4(b). As shown in Fig. 4(c), no matter how rotates the whole structure of the hybrid waveguide, its ultra strong optical field constraint is not affected, and the energy of the waveguide propagation is still concentrated in the middle layer of the three-layer structure. Figure 4(d) presents the comparison of coupling length for different waveguides positions. The coupling length of the rotated waveguides is significantly longer than that of the conventional ones at the same separation distance. As expected, for these two waveguides systems, the slope of the curve in the graph is almost the same, because they are composed of the same basic unit waveguide. Furthermore, the comparison of the maximum transfer power for different waveguides positions is shown in Fig. 4(e). This result also verifies that increasing of coupling length can reduce crosstalk.

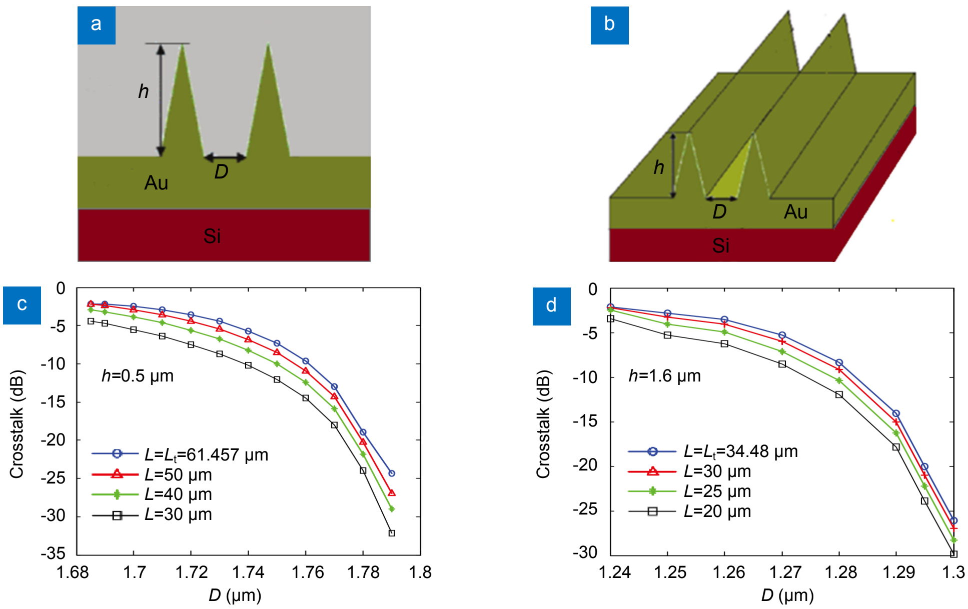

Fig. 3 | (**a**) The 2D and (**b**) 3D schematic diagrams of two WPP waveguides. Normalized crosstalk power of WPP waveguides under different parameters with wedge height (**c**) *h*=0.5 μm and (**d**) *h*=1.6 μm[32].

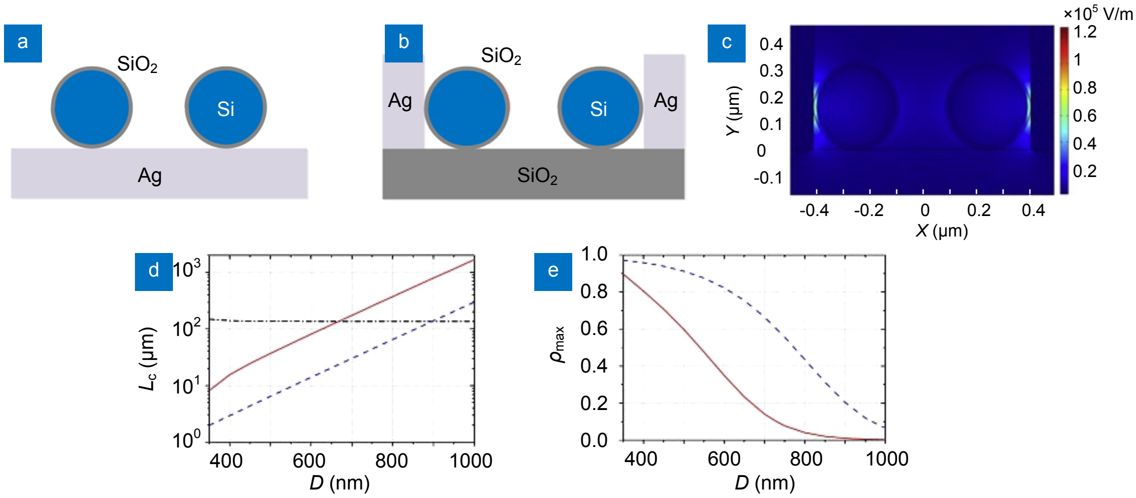

Fig. 4 | Schematic diagrams of (a) hybrid waveguide and (b) its rotation, (c) distribution of E_y field for rotation hybrid waveguide, (d) coupling length L_c and (e) maximum power transfer P_{max} as functions of the separation D, the red solid line and blue dotted line represent the results of the two structures of (a) and (b), respectively[25].

Obviously, this approach of reducing crosstalk by changing the relative position can be well applied to the hybrid waveguides with complex structure, but it may not work well when the waveguide structure is simple. Moreover, this approach may increase the difficulty of fabrication, and the transmission characteristics of the original waveguide should be maintained as much as possible when changing the relative position. By adjusting the relative position of the hybrid waveguides, the crosstalk can be further reduced, and the ultradense integration PICs could be realized without changing the transmission characteristics of the waveguide.

Approach of reducing crosstalk—inserting medium

Using a metallic strip

The approach of reducing crosstalk by changing waveguide placement has a limit in a certain extent, and it is unfavorable to increase the packing density of dense integration. In order to avoid aforementioned fault, Shruti et al.[30] put forward an alternative and effective approach. By inserting a metallic strip between two plasmonic waveguides, they proposed a hybrid waveguide structure and investigated the crosstalk.

As shown in Fig. 5(a), the hybrid waveguide structure consists of three layers of materials: Si, SiO_2 and Ag. By inserting the metallic strip between the two waveguides (Fig. 5(b)), the crosstalk has been reduced. They used the maximum transfer power P_{max} to evaluation the crosstalk. The crosstalk is affected by the height h and the width w of the metallic strip, and the variation of maximum transfer power of different h and w with the fixed separation distance D of 200 nm is shown in Fig. 5(d). The maximum transfer power of two waveguides decreases sharply as the metallic strip become wider and higher, which is more effective than increasing the separation distance (Fig. 5(c)).

This approach is mainly based on the principle that the field attenuation in the dielectric is much slower than that in the metal. And more notably, the insertion of a metallic strip between the two waveguides not only causes a certain energy loss for the transmitting energy of waveguides, but also greatly increases the difficulty for

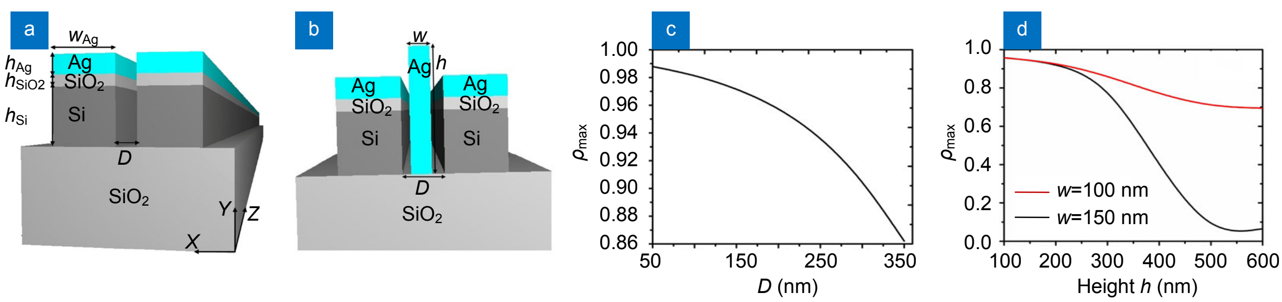

Fig. 5 | Schematic configuration of the two parallel hybrid silicon plasmonic waveguides (HSPW) (a) without and (b) with metallic strip. The maximum power transfer P_{max} versus specific parameters (separation distance D, height h and width w of the metallic strip) (**c**) without and (**d**) with metallic strip[30].

fabrication of the device. However, in the same size space of PICs, the crosstalk between the two plasmonic waveguides is significantly lower than that without the metallic strip.

Placing an auxiliary waveguide

In addition to inserting metal strips, the auxiliary waveguide can also be inserted to help reduce crosstalk. Kuznetsov E V et al.[33] adopted an auxiliary linear waveguide between two dielectric nanowaveguides to suppress the crosstalk (Fig. 6(a)). In particular, the crosstalk is suppressed by matching the wavenumbers of the propagation modes, which are the sum and difference of symmetric modes and antisymmetric modes in coupled system. They presented the optimized parameters of the auxiliary waveguide through numerical analysis.

The added auxiliary waveguide has only a small amount of energy compared to the waveguide with initial energy. In order to clarify the effect of auxiliary waveguide on crosstalk suppression, the distribution of the absolute value of the electric field in each waveguide is shown in Figs. 6(b) and 6(c). The energy transfer between the two adjacent waveguides is notable at a relatively short propagation distance without the auxiliary waveguide (Fig. 6(c)). Conversely, the energy transfer is obviously weakened in the same propagation distance with the auxiliary waveguide (Fig. 6(b)). It is noteworthy that this approach of reducing crosstalk needs to match the propagation modes of the coupled system composed of waveguides. The matching conditions are harsh and not applicable for all types of waveguides. Although this approach has its limitations, its advantages are obvious. In a word, the addition of auxiliary waveguide greatly increases the crosstalk length between plasmonic waveguides, which means that the crosstalk between waveguides can be effectively reduced.

Discussions

To sum up, we have reviewed the research work of crosstalk between plasmonic waveguides. The theoretical studies involved in the evaluation of crosstalk are briefly reviewed. Generally, most methods for evaluating crosstalk closely relate to the impact of coupling length on crosstalk, that is, the larger the coupling length is, the smaller the crosstalk is. Therefore, crosstalk can also be roughly measured by calculating the coupling length between the two waveguides. Whereas, the three crosstalk evaluation methods listed in this paper focus on different parameters of the waveguides, which make it possible to evaluate crosstalk effectively by choosing the specific method reasonably according to different real applications. Moreover, the main approaches to reduce crosstalk have been illustrated as two categories with examples. One means is changing waveguide placement while the other one is inserting medium. Concerning changing waveguide placement, the transmission characteristics of the waveguide itself is not affected, but more space is taken up, which will reduce the integration of PICs. Conversely, when using the method of inserting medium, crosstalk between waveguides can be obviously reduced in smaller space. However, the inserted medium can weaken the transmission characteristics of waveguide to some extent, which will increase the loss of transmission energy. Facing real application, one should consider the characteristics of different types of waveguides and the actual circuit requirements simultaneously, thus to choose appropriate crosstalk suppression method which is beneficial to improve the density of PICs.

It is widely believed that plasmonic waveguide has potential applications in optical interconnection due to its low crosstalk. Crosstalk is an inevitable issue we have to pay close attention to in PICs and optical interconnection applications. Except for the aforementioned methods, there are other similar extended methods can be considered. For example, when applying the approach of inserting metallic strips, silver strips could be replaced with gold or aluminum. Regarding the approach of placing auxiliary waveguide, different materials and different structures other than silicon waveguide could be introduced. Although we mainly review the crosstalk between two adjacent waveguides, it also lays a foundation for the study of crosstalk between multiple waveguides, such as triple-waveguide coupler[47]. In addition, it can be used as a reference exploring the optimized structure of graphene

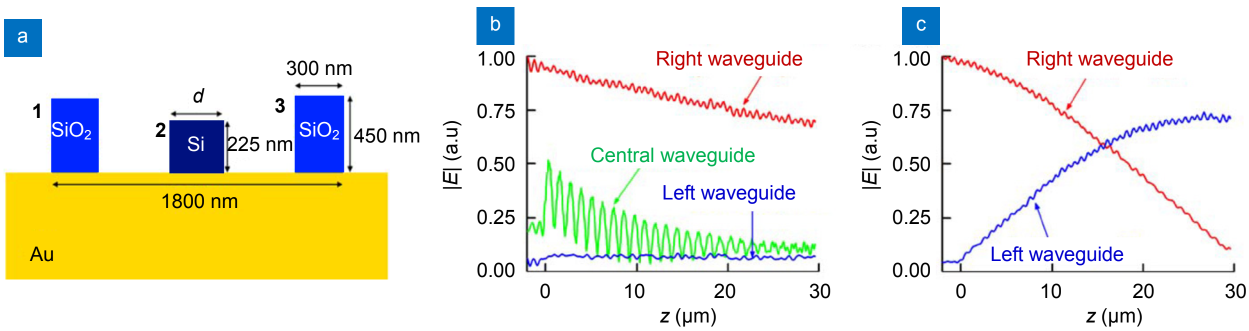

Fig. 6 | (**a**) The schematics of the surface plasmon waveguide system with the auxiliary waveguide. The distribution of the absolute values of the electric fields at waveguides (**b**) with and (**c**) without the auxiliary waveguide[33].

plasmonic waveguides[48,43]. Ref.[49] proposed an original method for coupling control by using adiabatic elimination scheme, and it provided a new way in achieving dense optical waveguiding with negligible crosstalk. In short, we believe that the crosstalk research between plasmonic waveguides would work for crosstalk study of other type waveguides, and provide references for design of waveguides and relevant devices used in PICs and optical interconnection fields.

References

1. Gramotnev D K, Bozhevolnyi S I. Plasmonics beyond the diffraction limit. *Nat Photonics* **4**, 83–91 (2010).
2. Ozbay E. Plasmonics: merging photonics and electronics at nanoscale dimensions. *Science* **311**, 189–193 (2006).
3. Dokania R K, Apsel A B. Analysis of challenges for on-chip optical interconnects. In *Proceedings of the 19th ACM Great Lakes Symposium on VLSI* 275–280 (ACM, 2009); http://doi.org/10.1145/1531542.1531607.
4. Miller D A B. Device requirements for optical interconnects to silicon chips. *Proc IEEE* **97**, 1166–1185 (2009).
5. Piliarik M, Homola J. Surface plasmon resonance (SPR) sensors: approaching their limits? *Opt Express* **17**, 16505–16517 (2009).
6. Maier S A, Kik P G, Atwater H A, Meltzer S, Harel E *et al*. Local detection of electromagnetic energy transport below the diffraction limit in metal nanoparticle plasmon waveguides. *Nat Mater* **2**, 229–232 (2003).
7. Charbonneau R, Lahoud N, Mattiussi G, Berini P. Demonstration of integrated optics elements based on long-ranging surface plasmon polaritons. *Opt Express* **13**, 977–984 (2005).
8. Berini P. Long-range surface plasmon polaritons. *Adv Opt Photonics* **1**, 484–588 (2009).
9. Steinberger B, Hohenau A, Ditlbacher H, Stepanov A L, Drezet A *et al*. Dielectric stripes on gold as surface plasmon waveguides. *Appl Phys Lett* **88**, 094104 (2006).
10. Chen Z, Holmgaard T, Bozhevolnyi S I, Krasavin A V, Zayats A V *et al*. Wavelength-selective directional coupling with dielectric-loaded plasmonic waveguides. *Opt Lett* **34**, 310–312 (2009).
11. Bozhevolnyi S I, Volkov V S, Devaux E, Laluet J Y, Ebbesen T W. Channel plasmon subwavelength waveguide components including interferometers and ring resonators. *Nature* **440**, 508–511 (2006).
12. Volkov V S, Bozhevolnyi S I, Devaux E, Laluet J Y, Ebbesen T W. Wavelength selective nanophotonic components utilizing channel plasmon polaritons. *Nano Lett* **7**, 880–884 (2007).
13. Pile D F P, Ogawa T, Gramotnev D K, Okamoto T, Haraguchi M *et al*. Theoretical and experimental investigation of strongly localized plasmons on triangular metal wedges for subwavelength waveguiding. *Appl Phys Lett* **87**, 061106 (2005).
14. Boltasseva A, Volkov V S, Nielsen R B, Moreno E, Rodrigo S G *et al*. Triangular metal wedges for subwavelength plasmon-polariton guiding at telecom wavelengths. *Opt Express* **16**, 5252–5260 (2008).
15. Gramotnev D K, Vernon K C, Pile D F P. Directional coupler using gap plasmon waveguides. *Appl Phys B* **93**, 99–106 (2008).
16. Tanaka K, Tanaka M, Sugiyama T. Simulation of practical nanometric optical circuits based on surface plasmon polariton gap waveguides. *Opt Express* **13**, 256–266 (2005).
17. Veronis G, Fan S H. Guided subwavelength plasmonic mode supported by a slot in a thin metal film. *Opt Lett* **30**, 3359–3361 (2005).
18. Oulton R F, Sorger V J, Genov D A, Pile D F P, Zhang X. A hybrid plasmonic waveguide for subwavelength confinement and long-range propagation. *Nat Photonics* **2**, 496–500 (2008).
19. Dai D X, He S L. A silicon-based hybrid plasmonic waveguide with a metal cap for a nano-scale light confinement. *Opt Express* **17**, 16646–16653 (2009).
20. Fujii M, Leuthold J, Freude W. Dispersion relation and loss of subwavelength confined mode of metal-dielectric-gap optical waveguides. *IEEE Photonics Technol Lett* **21**, 362–364 (2009).
21. Zia R, Selker M D, Catrysse P B, Brongersma M L. Geometries and materials for subwavelength surface plasmon modes. *J Opt Soc Am A* **21**, 2442–2446 (2004).
22. Liu L, Han Z H, He S L. Novel surface plasmon waveguide for high integration. *Opt Express* **13**, 6645–6650 (2005).
23. Veronis G, Fan S H. Crosstalk between three-dimensional plasmonic slot waveguides. *Opt Express* **16**, 2129–2140 (2008).
24. Bian Y S, Zheng Z, Zhao X, Zhu J S, Zhou T. Symmetric hybrid surface plasmon polariton waveguides for 3D photonic integration. *Opt Express* **17**, 21320–21325 (2009).
25. Song Y, Yan M, Yang Q, Tong L M, Qiu M. Reducing crosstalk between nanowire-based hybrid plasmonic waveguides. *Opt Commun* **284**, 480–484 (2011).
26. Xiao J, Liu J S, Zheng Z, Bian Y S, Wang G J *et al*. Low-loss metal-insulator-semiconductor waveguide with an air core for on-chip integration. *Opt Commun* **285**, 3604–3607 (2012).
27. Devaux E, Bozhevolnyi S I, Ebbesen T W, Volkov V S, Zenin V A *et al*. Directional coupling in channel plasmon-polariton waveguides. *Opt Express* **20**, 6124–6134 (2012).
28. Han Z H, Bozhevolnyi S I. Radiation guiding with surface plasmon polaritons. *Rep Prog Phys* **76**, 016402 (2013).
29. Huang C C. Ultra-long-range symmetric plasmonic waveguide for high-density and compact photonic devices. *Opt Express* **21**, 29544–29557 (2013).
30. Shruti R K S, Bhattacharyya R. Coupling and crosstalk characteristics of hybrid silicon plasmonic waveguides. *Appl Phys B* **116**, 241–248 (2014).
31. Chen L, Zhang T, Hong W, Zhou X, Li X. A graphene-based hybrid plasmonic waveguide with ultra-deep subwavelength confinement. *Journal of Lightwave Technology* **32**, 4199–4203 (2014).
32. Ma A N, Li G J, Li Y E. Crosstalk and coupling analysis of wedge plasmon polariton waveguides by the improved coupled mode theory. *J Nanoelectron Optoelectron* **10**, 828–832 (2015).
33. Kuznetsov E V, Merzlikin A M, Zyablovsky A A, Vinogradov A P, Lisyansky A A. Suppression of crosstalk in coupled plasmonic waveguides. arXiv:1611.08214 [physics.optics] (2016).
34. He X Q, Ning T G, Lu S H, Zheng J J, Li J *et al*. Ultralow loss graphene-based hybrid plasmonic waveguide with deep-subwavelength confinement. *Opt Express* **26**, 10109–10118 (2018).
35. Holmgaard T, Chen Z, Bozhevolnyi S I, Markey L, Dereux A. Design and characterization of dielectric-loaded plasmonic directional couplers. *J Lightw Technol* **27**, 5521–5528 (2009).
36. Kwon M S. Metal-insulator-silicon-insulator-metal waveguides compatible with standard CMOS technology. *Opt Express* **19**, 8379–8393 (2011).
37. Bian Y S, Gong Q H. Optical performance of one-dimensional hybrid metal–insulator–metal structures at telecom wavelength.

Opt Commun **308**, 30–35 (2013).
38. Bian Y S, Zheng Z, Zhao X, Liu L, Su Y L *et al*. Dielectrics covered metal nanowires and nanotubes for low-loss guiding of subwavelength plasmonic modes. *J Lightw Technol* **31**, 1973–1979 (2013).
39. Hao R, Cassan E, Xu Y, Qiu M, Wei X C *et al*. Reconfigurable parallel plasmonic transmission lines with nanometer light localization and long propagation distance. *IEEE J Sel Top Quantum Electron* **19**, 4601809 (2013).
40. Hao R, Peng X L, Chen H S, Yin W Y, Li E P. Plasmonic transmission lines with zero crosstalk. In *Proceedings of 2016 Asia-Pacific International Symposium on Electromagnetic Compatibility* 1021–1023 (IEEE, 2016); http://doi.org/10.1109/APEMC.2016.7522934.
41. Dolatabady A, Granpayeh N. Plasmonic directional couplers based on multi-slit waveguides. *Plasmonics* **12**, 597–604 (2017).
42. Nakayama K, Tonooka Y, Ota M, Ishii Y, Fukuda M. Passive plasmonic demultiplexers using multimode interference. *J Lightw Technol* **36**, 1979–1984 (2018).
43. Joshi S, Nehra V, Kaushik B K. Modeling and simulation analysis of graphene integrated silicon waveguides. *Proc SPIE* **10345**, 1034518 (2017).
44. Kwon M S, Kim Y. Theoretical investigation of intersections of metal-insulator-silicon-insulator-metal waveguides. *IEEE Photonics J* **8**, 2701510 (2016).
45. Liu J, Xiao J, Zhu J, Liu L, Zhou T *et al*. Dielectrics covered metal nanowires and nanotubes for low-loss guiding of subwavelength plasmonic modes. *Journal of Lightwave Technology* **31**, 1973–1979 (2013).
46. Zhou W, Huang X G. Long-range air-hole assisted subwavelength waveguides. *Nanotechnology* **24**, 235203 (2013).
47. Jiang W F, Cheng F Y, Xu J, Wan H D. Compact and low-crosstalk mode (de)multiplexer using a triple plasmonic-dielectric waveguide-based directional coupler. *J Opt Soc Am B* **35**, 2532–2540 (2018).
48. Cui J, Sun Y, Wang L, Ma P J. Graphene plasmonic waveguide based on a high-index dielectric wedge for compact photonic integration. *Optik* **127**, 152–155 (2016).
49. Mrejen M, Suchowski H, Hatakeyama T, Wu C H, Feng L *et al*. Adiabatic elimination-based coupling control in densely packed subwavelength waveguides. *Nat Commun* **6**, 7565 (2015).

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Competing interests

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