Abstract—The slot waveguide has attracted considerable attention because of its ability to confine and guide electromagnetic energy at the subwavelength scale beyond the diffraction limit. We propose a novel terahertz slot waveguide structure to achieve a better trade-off between propagation length and field confinement capacity, the novel waveguide consisting of a two slot structure. The performances of terahertz waveguides were investigated using the finite-element method. The results demonstrated that the hybrid slot waveguide (HSW) provides significantly enhanced field confinement in low index slot regions: more than five times that of traditional low index slot waveguides (LISWs). An optimized HSW structure was achieved by tuning the trade-off between mode confinement and propagation length. We also showed that its integration in conventional planar waveguide circuits was greatly improved compared with the LISWs, by comparing their crosstalk. The proposed new HSW structure has great potential to enable THz production of compact integration and could lead to true semiconductor-based THz applications with high performance.

Index Terms—Terahertz radiation, slot THz waveguide, enhanced field, propagation length, crosstalk.

I. INTRODUCTION

T ERAHERTZ waveguides have attracted significant attention in recent years due to their potential applications in a variety of areas, such as pharmaceutical quality control [1], [2], medical diagnostics [3], [4], imaging [5]–[7] and sensory applications [8]–[10]. Terahertz radiation (THz), which is situated between infrared and microwave radiation on the electromagnetic spectrum, typically refers to frequencies from 100 GHz to 30 THz [3], [4], [11]. With the commercialization of terahertz wave sources and detectors as an essential part of terahertz science and technology, THz waveguides have attracted considerable attention and their investigation has rapidly progressed in recent years [12]. During the past few decades, many researchers attempted to development the dual goal of low loss and smaller-sized THz waveguides. Examples include dielectric waveguides [13]–[17], metallic waveguides [18]–[21] and plasmonic waveguides [22], [23]; these structures have all been theoretically proposed or experimentally demonstrated. Among the wide variety of THz waveguide structures being investigated, plasmonic structures can achieve a better trade-off between propagation length and confinement capacity. In addition, plasmonic waveguides can break through the diffraction limitation and achieve a smaller physical size. However, surface plasmon polaritons (SPPs) only give subwavelength field localization for frequencies close to the intrinsic plasma frequency of the conductor [19]. In the THz regime, metals are nearly a prefect conductor and negligible penetration of electromagnetic fields leads to highly delocalized surface plasmon polaritons [19], [24]. Besides this, the problem of loss in THz waveguide has become the largest obstacle for migration from theoretical predictions to practical implementations.

In order to provide a solution for the above problem, we propose a novel layer-by-layer metal–semiconductor–slot–semiconductor–metal structure that we call a hybrid slot waveguide (HSW), because the silicon-slot-silicon was superimposed over a metal-slot-metal. The characteristics of its integration properties were investigated using the finite-element method. Firstly, we studied the electric field distribution of fundamental slot modes and the dual-plasmonics slots effect; the low-index polyethylene (LDPE) layer showed a good subwavelength in THz field confinement. To find out the appropriate layer height for the HSW, the effect of the height on field confinement and field distribution was analysed. After that, the field confinement of our proposed HSW structure was further investigated by comparing it with the low-index slot waveguides (LISWs) which have a low-index slot layer embedded in a homogeneous high-index material. Finally, the properties of on-chip integrations(crosstalk) with the HSW structure were also studied and compared with the LISW structure. The proposed HSW structure was easy to fabricate using layer-by-layer deposition and formation by chemical etching. It exhibits improved crosstalk between two same waveguides in THz circuits.

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Ultra-strong field enhancement in the vertical direction was observed in the low-index LDPE layers, which is beneficial for the low-index slot, with $H_t = 10 \mu m$, embedded between the Si layers. Furthermore, an intensity enhancement of the electric field was also presented between the two plasmonics structures made of Si layers and Au layers, because the field enhancement at the boundary in the low-index region came from a hybrid effect of Si and Au. This structure is capable of realizing a high confinement factor for a quasi-TM mode. The coupling issues in such waveguide is a challenge, but it can be solved according to some reference [26], [27].

To further characterize the working performances, we compared the field confinement capability of the HSW structure with LISW at different widths. Here, we set $H_t = 60 \mu m$, $H_{Si} = 5 \mu m$, $H_{Au} = 10 \mu m$. In order to further investigate the HSW’s behavior in field confinement, the confinement factor was defined as $Q = P_1/P_2$, where $P_1$ is the power density inside the low-index slot regions and $P_2$ is the power density which is distributed throughout the structures. The confinement factor ($Q$) versus the height ($H_t$) of the low-index layers for both HSW and LISW was plotted and shown in Fig. 3. It is evident that the values of $Q$ for HSW and LISW exhibited similar changes depending on $H_t$. The values of $Q$ for HSW increased with the increase of $H_t$ from 1 to 10 $\mu m$. At $H_t = 15 \mu m$, the value reached a maximum of 64.47%; after that, it remained at about the same value. For LISW, the variation of $Q$ had a similar trend to HSW within the range of $H_t$ from 1 to 11 $\mu m$. At $H_t = 11 \mu m$, the value of $Q$ for LISW reached a maximum of 15.09%; after that, it decreased with increasing $H_t$. It is important to note that the value of $Q$ for HSW was much higher than that of LISW at the range of $H_t$ from 1 to 35 $\mu m$. For instance, the fundament modal profiles for both HSW and LISW at $H_t = 11 \mu m$ and 30 $\mu m$ have been shown in the insets of Fig. 3 and it is notable that at $H_t = 30 \mu m$, HSW has kept a good field confinement capability, while LISW has less energy in the low index layer. These results demonstrate that the field confinement capability of the HSW is better than that of the traditional LISW. Two effects on the field confinement property are associated with the proposed HSW structure. One is that more energy can be confined in the slot between the plasmonics structure than the slot in the silicon. The other is that some
energy can overflow from the middle layer to the Si layer in LISW structure due to the slot area comprised of silicon. A substantial amount of THz electromagnetic energy can be held in the slot region; a structure with this property has promising use in various practical applications such as high-speed communication, molecular spectroscopy, security imaging and medical diagnosis.

As found above, the HSW structure can provide enhanced field confinement. However, field enhancement means that the propagation length will decline [28], [29]. Therefore, the design was optimized to provide a better tradeoff between field confinement and propagation loss [29]. THz electromagnetic energy can be transmitted in the silicon, so the height of the silicon area is an important factor in the properties of the proposed waveguide. The parameter of silicon’s height (Hsi) can control the field confinement properties of the HSW, which was set to 5 μm, 10 μm, 15 μm, and 20 μm. The properties of the HSW were affected by the slot ridge between two silicon layers. The confinement ability can be expressed as the normalized effective mode area (Aeff/A0), where A0 is the diffraction-limited mode area in free space, defined as λ2/4. Therefore the target parameters of optimization were Aeff/A0 and the propagation length (L). The propagation length of structure was defined as

\[ L = \frac{\lambda}{4\pi \text{Im}(n_{\text{eff}})} \]  

(1)

where neff is the complex modal effective index, and the effective mode area Aeff was calculated by

\[ A_{\text{eff}} = \frac{\int W(r) dA}{\text{max}(W(r))} \]  

(2)

where the electromagnetic energy density \( W(r) \) was defined as [14]

\[ W(r) = \frac{1}{2} \text{Re} \left\{ \frac{d[\omega \varepsilon(r)]}{d\omega} \right\} \left| E(r) \right|^2 + \frac{1}{2} \mu_0 |H(r)|^2 \]  

(3)

where E(r) and H(r) are the electric and magnetic fields, \( \varepsilon(r) \) is the electric permittivity, and \( \mu_0 \) is the vacuum permeability or magnetic constant. To compare the performance of different configurations, a figure of merit (FOM) was introduced, which was defined as: FOM = L/[2(Aeff/\pi)^1/2]. The effect of Ht and Hsi on Im(n_{eff}), L, Aeff/A0 and FOM is shown in Fig. 4(a)–(d), respectively. From Fig. 4(a), it can be seen that when Ht < 20 μm, Im(n_{eff}) decreased as Hsi increases, implying that the transmission loss decreased with the increase of Hsi. On the contrary, when Ht < 20 μm, the propagation length (L) always increased with the increase of Hsi [see Fig. 4(b)]. It is noted that the value of Im(n_{eff}) and L tend to be stable, showing that the loss of propagation was independent of Ht.

We also observed that Aeff/A0 can be enhanced by increasing Hsi, Ht, or both, as shown in Fig. 4(c), which means the field confinement capability has a negative dependence on Hsi, Ht, or both. This is because the ability of metal to confine electromagnetic energy is greater than that of non-metals. Even when Hsi = 20 μm, the electromagnetic energy was confined to the subwavelength area.

Using the L/Ht data in Fig. 4(b) together with the (Aeff/A0)/Ht data in Fig. 4(c), it was possible to derive the relationship between FOM and Ht for each Hsi, as shown in Fig. 4(d). FOM increased with increasing Ht, when Hsi = 5 μm and Hsi = 10 μm. However, FOM decreased with Hsi = 15 μm and Hsi = 20 μm. Based on the data of Fig. 4(d), the optimal HSW configuration with the best tradeoff between field confinement (Aeff/A0 = 0.169) and propagation length (L = 14.23 mm) was achieved at HAu = 60 μm, Hsi = 20 μm, and Ht = 5 μm. In this case, neff was 1.758.

The integration properties of slot waveguide structures can be characterized by crosstalk. In the following text, the crosstalk of the optimized HSW structure is evaluated. Because of the existence of metal on the top of the structure, the crosstalk in the vertical direction is relatively small. Hence, only horizontal crosstalk was investigated to predict the integration properties. The crosstalk can be featured by the coupling length (Lc) and the maximum transfer power (P_{max}). The coupling length Lc can be calculated by [30]–[32]

\[ L_c = \frac{\pi}{|k_s - k_a|} \]  

(4)

where \( k_s \) and \( k_a \) are the wavenumbers of the symmetric and anti-symmetric modes of two coupled waveguides, respectively. The maximum transfer power is a function of Lc [32]

\[ P_{\text{max}} = \frac{\exp \left(-2 * x * \arctan \left(x^{-1}\right)\right)}{1 + x^2} \]  

(5)

where

\[ x = 2L_c / (\pi L_P) \]  

(6)

if \( L_P \) is the mean attenuation length of the symmetric and anti-symmetric modes of two couple waveguides.

In order to calculate the coupling length and maximum transfer power, the anti-symmetric and symmetric crosstalk systems (which consist of two identical HSW waveguides) were built as schematically shown in Fig. 5(a) and (b), respectively.
confinement capability in the HSW structure which can help to reduce the mode overlap between two waveguides. Our results revealed that the proposed HSW structure can provide higher density integration in integrated photonic circuits.

IV. CONCLUSION

To develop THz integration technology, a novel terahertz slot waveguide structure has been proposed and its field mode characteristics and horizontal crosstalk have been investigated using the finite element method. Comprehensive theoretical computations showed that the proposed slot waveguide structure is capable of enhancing electromagnetic confinement at THz wavelengths ($\lambda = 0.3$ mm) as compared to LISWs, because the plasmonics slot function is guarded by semiconductors and metal. Optimization of the HSW structure achieves 2D tight mode confinement with relatively low propagation loss (the propagation length can reach 14.23 mm). Moreover, the optimized HSW structure exhibits better planar integration (crosstalk) properties than that of LISWs, providing the capability for high density integration in Si-based electronic circuits and planar THz wave circuits. Our proposed HSW structure can be made using a standard Si fabrication process and has the potential to enable the production of compact THz components.

REFERENCES

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