Dispersion characteristics of channel plasmon polariton waveguides with step-trench-type grooves

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Abstract: We have studied the dispersion characteristics of single-mode channel plasmon polaritons (CPPs) with step-trench-type groove waveguides. From the numerical simulations using the finite-element method, the modal shapes and the complex propagation constants of the CPPs over a wide spectral range were obtained. It is shown that the dispersion characteristics of the step-trench-type CPP waveguide, which is composed of a step trench with a stacking nature, show an intermediate feature between the narrow and broad trenches. The results show that this configuration allows for a well-confined CPP with a moderate propagation loss at the wavelengths investigated.

OCIS codes: (240.6680) Surface plasmons; (230.7380) Waveguides, channeled; (250.5300) Photonic integrated circuits

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1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves that are bound to a metal-dielectric interface and are coupled to the oscillations of the free electrons in the metal [1]. There has been much interest in utilizing SPPs, because electromagnetic waves are able to be confined in a small cross-section located perpendicular to their direction of propagation while most of their energy is confined to the interface [2-4].

In particular, there have been many suggestions of SPP waveguide structures that can implement highly confined electromagnetic waves able to be propagated with a moderate loss [3, 5-7]. For example, long-range SPPs (LRSPPs) based on thin metal films or stripes have been intensively investigated [6]. However, this type of waveguide is limited in high integration for wide field extension to the surrounding dielectric media [2, 6]. In contrast, by using metal cladding, the field can be confined tightly in a small cross-section. Although the propagation length for this type of waveguide is generally limited to a few tens of micrometers, many investigations have been reported on this configuration, owing to its potential for high integration [7-15] and among these investigations, channel plasmon polaritons (CPPs) are especially interesting. Since the first theoretical proposition of CPPs [8], many experimental and theoretical investigations have been carried out [8-14]. Recently, experiments into CPPs utilizing optical devices operating at telecommunication wavelengths, such as waveguide bends, splitters, interferometers, and resonators have been reported [10, 15]. Among the various geometries that have been proposed, there have been two representative groove types: a triangular (V-shaped) type and a rectangular (trenched) type.

In this work, we discuss our proposal of a novel CPP waveguide configuration, a step-trench-type groove acting as a CPP waveguide, and discuss our investigations into its properties. The dispersion characteristics of CPPs in step-trench-type grooves, including the modal shapes, effective indices, and propagation lengths were obtained numerically using a finite-element method (FEM). In the following section, we will revisit the dispersion characteristics of V-shaped and trenched waveguides to review some important characteristics of CPPs. Then, an analysis on the dispersion characteristics of our proposed step-trench-type waveguide will be presented. Finally, a discussion on the advantages of our suggested configuration compared with conventional structures will be presented. Our discussion focuses on the practicality of the implementation of well-confined CPP waveguides for highly integrated optics.

2. The dispersion characteristics of conventional CPP waveguides

As a first step, we will briefly review several important characteristics of the two conventional CPP waveguide configurations. To examine the dispersion characteristics of CPPs in several geometries, we numerically simulated representative examples of conventional CPP waveguides by using FEM mode calculation method with COMSOL [16]. Through this paper, the effective index and the propagation length are defined as follows: $n_{eff} = \mathrm{Re}\left(\beta / k_0\right)$, and $L_{prop} = 1/\mathrm{Im}\left(\beta\right)$, where β and k_0 are complex propagation constants of SPP and free space, respectively.

The dispersion curves, along with their propagation lengths, are shown in Fig. 1. The geometrical parameters of the V-shaped waveguide were: depth d = 1.2 μm and top opening width w = 523 nm. These parameter values are close to optimum values for this type of

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waveguide [11, 12]. Then, we simulated CPPs in trench waveguides for two different opening widths, but with the same depth. For the wider trench, the opening width was selected to have the same value as the V-shaped case, $w = w_1 = 523$ nm, while for the narrow trench, $w = w_2 = 120$ nm. In all three cases, the groove depths were set to the same value. We adopted a gold metal substrate whose wavelength-dependent permittivity was assumed to follow the extended Drude model [17]. For the V-shaped groove, the sharpness of the tip played an important role in the modal distribution. Moreover, in the case of an infinitely sharp bottom tip, even the single-mode nature could be broken. To prevent this nonphysical situation occurring, we introduced a 5 nm-radius round-off at the bottom tip of the V-groove, which corresponded to about 14 segment points along the arc of the tip in the COMSOL simulations. For all other V-groove edges or any other configurations used in our work, we did not introduce any intentional round-offs in the numerical models. In all our simulations, the maximum length of the triangular meshes at the vertices of the groove and the metal-air interfaces were set to be no longer than 10 nm.

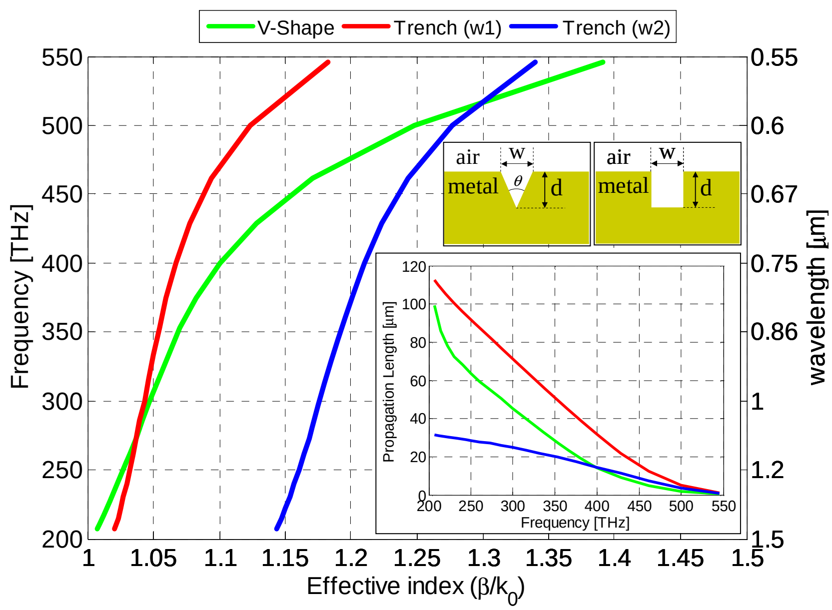

Fig. 1. The effective indices of the fundamental CPP modes in V-shaped, broad, and narrow trenches. The two upper insets show geometrical schematic drawings of the V-shaped (left) and trench (right) waveguides. The frequency-dependent propagation lengths for these configurations are depicted in the lower inset. The depth of all the geometries was set to the same value, $d = 1.2$ μm. The top-most opening widths were: $w = 523$ nm (V-shape), $w_1 = 523$ nm (trench), and $w_2 = 120$ nm (trench).

In Fig. 1, it can be seen that as the wavelength increases, the effective index becomes closer to the refractive index of the cladding dielectric material, (in this case, air). This is caused by the movement of the modal energy of the fundamental CPP mode towards the groove opening [12]. In this case, although the propagation length increases, the mode confinement becomes poorer. Hence, to establish a good confinement for the purpose of high integration, a deeper groove depth is required. On the other hand, for short wavelengths, although most of the modal energy is well confined inside the groove area, the propagation length decreases. In brief, there exists a trade-off relationship between the mode confinement and the propagation length of the CPPs. Besides the above features, when the opening of the channel waveguides becomes narrower, then the waveguide cannot maintain a single-mode nature [11, 12]. Hence, at least for single-mode operation over a wide wavelength range, generally speaking, deeper and wider channels are required, which may limit the size reduction capability of the highly integrated circuits.

Another topic that has to be considered is the difficulty in fabricating narrow and deep trenches or sharp V-grooves. To decrease this difficulty while benefiting from the good confinement over a wide spectral range, another type of structure is required. We suggest a step-trench configuration for such a CPP waveguide, which is discussed in the next section.

3. A step-trench CPP waveguide

A schematic diagram of our step-trench waveguide is shown in Fig. 2. This structure can be understood as two trenches with different widths forming a simple stack in the direction oriented vertically to the metal surface.

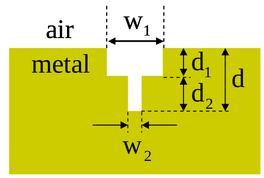

Fig. 2. A schematic diagram of our proposed step-trench waveguide.

The dispersion characteristics and corresponding propagation lengths of step-trench CPPs having different geometrical parameters are shown in Fig. 3. In our calculations, the top opening width, w_1, and the total groove depth, d, were set to the same values as the geometries shown in Fig. 1. The width of the narrow region, w_2, in Fig. 2 was also set to the same value as that shown in Fig. 1. By keeping the same width of the structures, we varied the depth, d_1, of the upper broad region from 200 nm to 1000 nm, while fixing the total depth of the groove as 1200 nm.

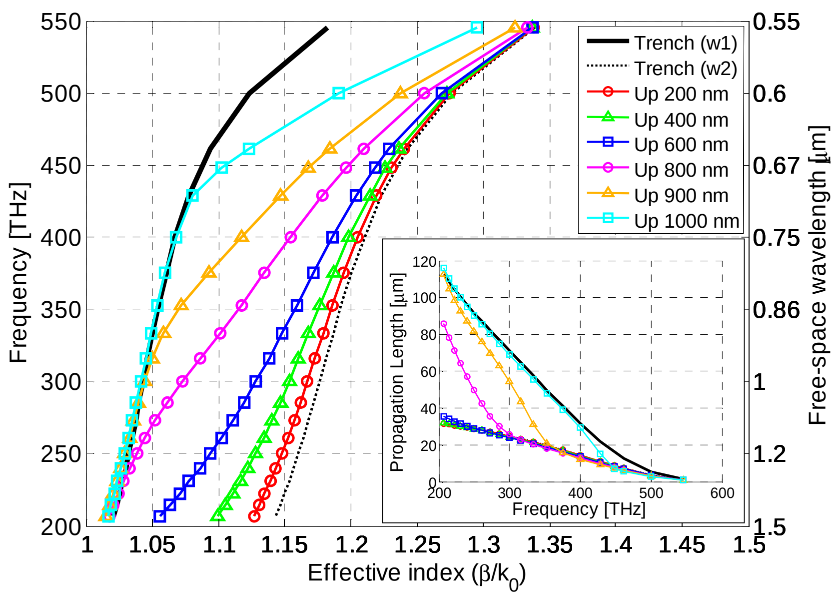

Fig. 3. The dispersion characteristics of step-trench-type CPPs for different depths. The inset shows the results for the corresponding propagation lengths. The upper trench depth, d_1, was varied from 200 to 1000 nm (depicted as 'Up 200 nm' – 'Up 1000 nm'). In all cases, the total depth was fixed at d = 1.2 μm. The results for the conventional trenches shown in Fig. 1 are represented as black lines.

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From the results shown in Fig. 3, it can be seen that the dispersion characteristics and the corresponding propagation loss of the CPPs in the step-trench-type grooves showed an intermediate feature between the two conventional trenches (having widths of w_1 and w_2) that form the structure. In the short wavelength regime, the modal energy is confined to the lower trench area, and hence, the dispersion characteristics resemble those of a narrow trench. In contrast, in the long wavelength regimes the modal energy leaks towards the channel opening, and the dispersion characteristics resembles a broad trench's properties. However, as shown in Fig. 3, the dispersion characteristics in the long wavelength regime are more easily influenced by changes in the depth. In other words, by varying the depth of the upper broad trench, the confinement of the long wavelengths can be enhanced while not affecting the behavior of the short wavelengths. This intermediate feature can be used as a simple, but important, guideline to determine the geometrical parameters.

In addition, this type of configuration can provide more than an increase in the degree of freedom in the design parameters, as the modal energy confinement is enhanced compared to other conventional CPP waveguide structures. We examined the wavelength-dependent mode power for several step-trench geometries to compare the modal energy confinement characteristics. Figure 4 shows the normalized modal energy distribution graphs and contours for -10 dB drops from the peak power for structures with three different geometries: V-shaped, trenched, and step-trenched. We used -10 dB drop lines instead of -3 dB drop lines for clear vision.

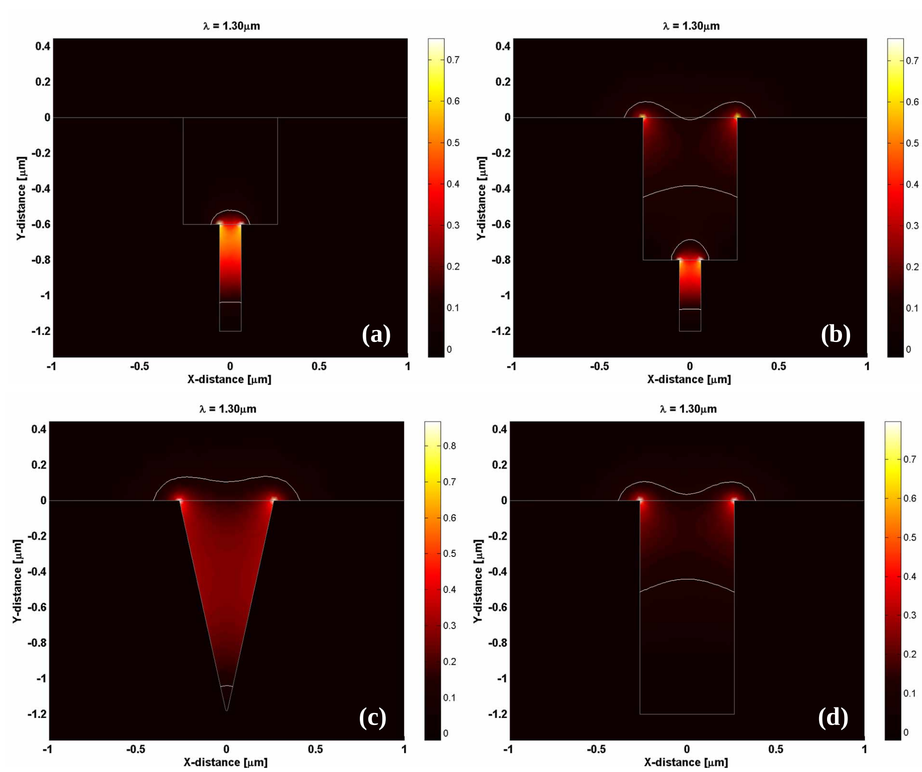

Fig. 4. (Movie) Normalized modal energy distribution. The white curves denote the contour lines for -10 dB power drops from the peak power, and the thin gray lines denote the geometrical boundaries. In all cases, the top opening width and the total groove depth were fixed to have the same values of 523 and 1200 nm, respectively. For the step trenches, the depth of the upper trench was: (a) 600 and (b) 800 nm. The width of the narrow lower trench in (a) and (b) was 120 nm. The wavelength-dependent evolution of the modal energy distribution are shown in movies with a file size of: (a) 211, (b) 218, (c) 249 and (d) 237 KB.

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As shown in Fig. 4, the modal energy of the step-trench-type waveguides was well confined inside the waveguide core area. For example, in Fig. 4(a), even when the modal energy of the V-shaped (Fig. 4(c)) or trenched (Fig. 4(d)) waveguides overflowed out of the groove wall at long wavelengths, the mode for the step-trench waveguide was well confined inside the groove, and this well-confined nature was obtained for a shallow depth configuration of the upper broad trench. However, as shown in Fig. 3, the propagation length of this configuration was not very long. On the other hand, for a deeper upper trench configuration, although the mode confinement was less than that of a broad trench, the propagation length was increased correspondingly.

We carried out further investigations into the mode confinement to obtain more insight into this trade-off between propagation length and mode confinement. Because of the surface wave nature of the SPPs, when we consider the mode confinement to estimate the coupling or crosstalk between two parallel waveguides, the main concern is the lateral (parallel to the *x*-axis in Fig. 4) mode diameter at the interface. We define the lateral mode radius r_{3dB} as the distance of -3 dB power drop point from the waveguide's symmetrical plane. Figure 5(a) shows the wavelength-dependent r_{3dB} variations over wavelength range.

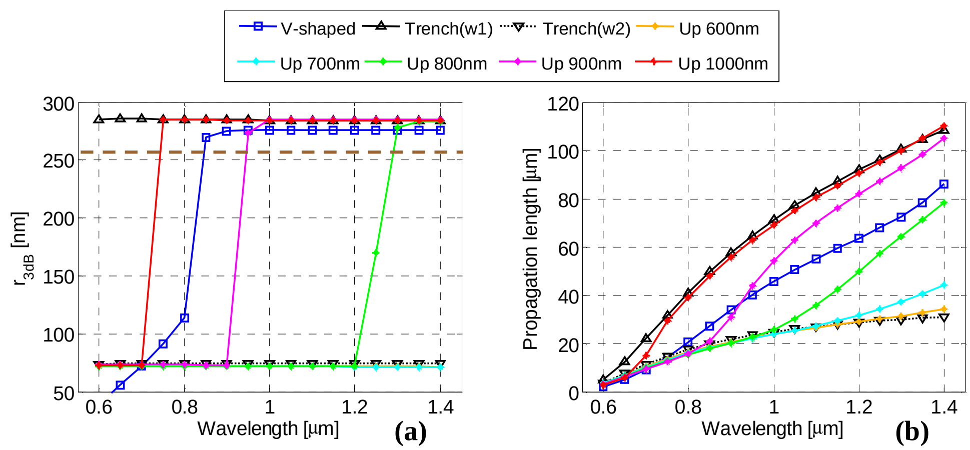

Fig. 5. Numerical results of: (a) the wavelength-dependent lateral mode radius, and (b) the propagation length. The brown horizontal line in (a) depicts a distance of half the opening-width of the waveguide (261.5nm).

As shown in Fig. 5(a), the value of r_{3dB} in the short wavelength regime corresponds to that of narrow trench. As the wavelength increases, an abrupt jump to large values of r_{3dB} (which corresponds to broad trench value) was observed. This abrupt jump originates from the increasing intensity of the wedge mode at the edge of the upper broad trench. This wedge mode effect can also be observed in V-shaped trenches in the wavelength range of 800–900 nm in Fig. 5(a), but from the discontinuous shape of the step-trench, the 'jump' occurs more suddenly in our proposed structure than in the V-shaped structure. As the depth of the upper trench in the step-trench waveguide increases, the wavelength of this abrupt jump shifts to lower values. This can be envisaged by considering that as the depth of the upper broad trench increases, the nature of the broad trench dominates. Although the saturated r_{3dB} values in the long wavelength regime are larger than those of a V-shaped waveguide, the propagation length in Fig. 5(b) shows that the propagation lengths in this regime are also larger than in V-shaped CPP waveguides. As mentioned above, the trade-off between mode confinement and the propagation length can be observed in Figs. 5(a) and 5(b). However, when compared to the V-shaped waveguide, one can find that for typical geometric configurations, both the

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smaller r_{3dB} and the longer propagation length can be achieved. For example, the 'UP 900 nm' configuration, as depicted by the purple line in Fig. 5, shows a longer propagation length with a smaller mode radius for operation wavelengths of about 900–1000 nm. Moreover, we expect that when the depth of the upper trench is carefully selected, this spectral range can be increased.

To treat the trade-off between several configurations, we defined a figure-of-merit (FOM) as,

$$FOM = \frac{Propagation\ length}{Lateral\ mode\ radius} = \frac{L}{r_{3dB}}. \quad (1)$$

From the definition in Eq. (1), a large value of FOM implies a long propagation length or a small mode radius. Our results are shown in Fig. 6.

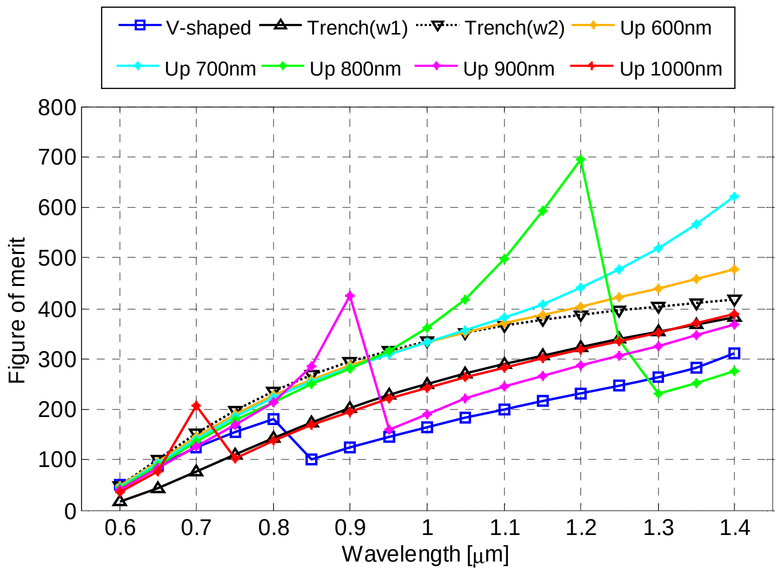

Fig. 6. Figure-of-merit for several waveguide configurations.

In Fig. 6, in most of our configurations, the value of the FOM was better than that of the V-shaped waveguide. Compared to a the broad trench waveguide, at shorter wavelengths before the occurrence of the abrupt jump shown in Fig. 5(a), the value of the FOM of step-trench-type structure is better. For example, for a configuration with a shallow upper trench, such as 'Up 600 nm' or 'Up 700 nm', the value of the FOM is superior over most of the spectral range. Here, we need to mention that the value of the FOM in the short wavelength regime is slightly worse than that of a narrow trench, even for shallow upper trench configurations. However, when we consider the fabrication process that needs to be applied for mass-production, such as 'nanoimprinting' [18, 19], our proposed step-trench configuration is the most appropriate choice versus the needs of fabricating a deep and narrow trench. Moreover, when the inter-waveguide crosstalk is the main parameter of concern rather than the propagation length, which is expected to be important in highly integrated applications at telecommunication wavelengths, a configuration such as 'Up 600 nm', as shown in Figs. 5 and 6, would be a good example that easily satisfies the requirements.

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4. Conclusions

We have suggested and numerically investigated the step-trench-type CPP waveguide configuration. From our results, our proposed waveguide structure shows an intermediate nature between its composing two (narrow and broad) trenches, which gives us a simple, but useful, guideline and more degrees of freedom in designing this type of waveguide. The mode confinement of the step-trench-type waveguide is better than that of conventional V-shaped or trenched waveguides with the same opening width when the geometrical parameters are properly selected. Considering the figure-of-merit defined to evaluate the trade-off between the mode confinement and the propagation length, our proposed structure shows an advantageous feature. Our proposed configuration is an appropriate structure for highly integrated photonic devices with a diminishing degree of difficulty during fabrication, compared to the case of making narrow and deep trenches.

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