A proposal design for robust and broadband microwave SPPs waveguide coupler via STIRAP

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Abstract. In this paper, we give a proposal to design a microwave Surface Plasmon Polaritons (SPPs) coupler, which can completely transfer energy of SPPs with robustness against varying geometrical parameters and broadband frequency range of microwave, based on Stimulated Raman Adiabatic Passage (STIRAP). The STIRAP is one of the most famous quantum coherent control methods, and most importantly it can improve the robustness of the device and energy transmission efficiency. This work is not only promising in designing robust and broadband compact microwave couplers, but also leading larger potential applications in microwave and millimeter wave communication.

1. Introduction

Surface Plasmon Polaritons (SPPs) are highly localized surface electromagnetic waves that propagate along the interface between the metal and the dielectric (the two materials have the opposite signs of the real part of electric permittivity), and decay exponentially in the transverse direction [1]. SPPs have promising applications in biomedical sensing [2], optical data storage [3]. Most recently, owing to their inherent properties of subwavelength scale and strong field enhancement, SPPs can be usually used to manufacture compact and integrated devices, for example, integrated SPPs waveguide couplers [5].

The Stimulated Raman Adiabatic Passage (STIRAP) is a quantum three-state system, which can achieve completely population transfer from an initial populated state to a target state via an intermediate state [6]. The STIRAP is one of the most famous quantum coherent control methods, which is usually used in atomic quantum systems [7] and many-body physics [8]. Since longhi firstly introduced the STIRAP into the optical waveguide [9], numerous works based on quantum-optical analogy have been investigated under his achievement [10, 11]. The robustness and broadband frequency range of our device comes from STIRAP. Based on the theory of STIRAP, the only condition of coupling strength (the delivery ability of SPPs from one waveguide to another one) between input (output) and middle SPPs waveguide C1 (C2) is that, at the beginning, C2 should be much larger than C1. At the end of device, C1 should be much smaller than C2 [6]. If there is sufficient overlap of the two coupling strengths (C1, C2) and the coupling strengths are strongly enough, the time evolution is adiabatic, then the complete population transfer occurs between initial state to target state [6]. Meanwhile, the coupling between the three SPPs waveguides can be described by coupled equations. By using approximation, we can derive the coupled equations as Schrodinger equation. Therefore, we can link our SPPs waveguide coupler and the atomic system. In the previous
research [12], it had already demonstrated this relationship. Thus, we can employ the STIRAP technique to design our SPPs waveguide coupler.

There are many works based on various structures of SPPs waveguide, both of them are sensitive to geometrical parameters [13, 14]. The slightly change of geometrical parameters can affect the propagation properties of SPPs waveguide. In order to overcome this issue, most recently, there are some remarkable papers showing the pathway of connecting STIRAP and SPPs waveguide coupler in Terahertz (THz) regime [12] and optical [15]. Based on these pioneer studies, thus, we can introduce the STIRAP into the design of SPPs waveguide coupler under the microwave regime, aiming to improve the robustness against the fluctuation of geometrical parameters of the waveguide coupler and operate in broadband frequency range of microwave.

2. Coupling strength between two parallel SPPs waveguides

Based on the theory of STIRAP, the counterintuitive ordering (the Stokes pulse precedes the pump pulse) guarantees a complete population transfer from an initially populated state to a target state via an intermediate state [6]. Therefore, in order to achieve our proposal design, the first step we need to do is acquiring the coupling strength between two parallel adjacent SPPs waveguides, and then we can design these two coupling strength functions as two Gaussian shapes (likes the shapes of Stokes pulse and pump pulse).

![Figure 1](image)

**Figure 1.** (a) The schematic illustrates the schematic of the two parallel corrugated metal waveguides. The blue part represents the substrate with a relative dielectric constant of 2.9 and yellow part represents metals, with geometrical parameters width W, thickness t, depth h, groove width a, periodic d, gap distance g and length L. (b) The yellow curve, brown curve, and blue curve represent coupling strength with frequency of 12 GHz, 11 GHz, and 10GHz, respectively.

Firstly, we need to configure out the coupling strength functions against different gap distances between two adjacent parallel SPPs waveguides. Based on the coupled mode theory (CMT), the coupling strength between two waveguides has the exponential relationship with the different gap distances. However, it is very tough to calculate the mode profile of the SPPs waveguide in analytical solution. Therefore, we employ the full-wave simulation of CST software to get the coupling strength functions. In this paper, we employ the metal structure in the ref. [1], as shown in Figure 1(a). The model is composed of two parallel corrugated metal strips with thickness of t and width W, of which
one side is corrugated by one dimensional arrays of grooves with depth h, width a, and periodic d. We set the parameters depth h, width a, thickness t, width W and periodic d as 4mm, 2mm, 0.018mm, 5mm, and 5mm. In the parallel configuration, we can measure the complete transfer SPPs energy distance (coherent length $L_c$) from the CST simulation. Subsequently, we can calculate the coupling strength C, by using $C = \pi/2L_c$. In the full-wave simulation commercial software CST, the corrugated waveguide is represented by PEC, because the metal behaves as PEC under the ultraviolet frequency range. And the boundaries of all directions are set “open” in order to simulate the real space.

The coupling strength functions are shown in Figure 1(b), these curves illustrate the functions between coupling strength and different gap distances with the incident frequency of 10 GHz, 11 GHz, 12 GHz. From the Figure 1(b), the coupling strength functions of two parallel SPPs waveguides have the exponential relationship against the gap distance based on the simulation results of CST. Therefore, our result (Figure 1(b)) is consistent with the theory of CMT. Furthermore, when the frequency of input microwave increases, the coupling strength enhances with the same gap distance and it is the same as the ref. [1]. To sum up, we believe that our result of coupling strength is a good approximation for this model. Then, we can design the $C_1$($C_2$) as we talked before.

3. STIRAP in three SPPs waveguide coupler
In this paper, we design two corrugated curved SPPs waveguides with radius R and one straight SPPs waveguide coupler based on STIRAP, in which can support SPPs energy completely transfer and achieve the robustness [6] against the fluctuation of geometrical parameters of the waveguide coupler. The schematic of our proposed device shows in Figure 2. Noticed that the offset between two centers of circles (input and output SPPs waveguides) in the x axis is $\delta$ and center of output SPPs waveguide is on the left of the center of input SPPs waveguide (in the direction of x axis).

![Figure 2. The schematic of our proposed design. The $d_{\text{min}}$ is the minimum distance between input/output SPPs waveguide and middle SPPs waveguide and these two minimum distances has the mismatching distance $\delta$. The input and output SPPs waveguides have the curve with radius R.](image)

Based on the results we calculated in the section 2, we can verify that our result is consistent with CMT, then the coupling strength function can be approximated to Schrödinger equation. Therefore the STIRAP can be used in designing the SPPs waveguide coupler. To be more clearly described, we give an example. The parameters of our model is set as radius R = 5 m, mismatching distance $\delta = 0.5$ m, minimum distance $d_{\text{min}} = 1$ mm and device length $L = 2$ m. The distance layout (the distance between input/output and middle SPPs waveguide in the vertical direction) of the input/output and middle SPPs waveguide is shown in Figure 3(a). Therefore, we can obtain the coupling strength functions between
input (and output) SPPs waveguide and middle SPPs waveguide, corresponding to our designed geometrical parameters, as shown in Figure 3(b). Subsequently, we can retrieve the energy transfer evolution of three (input, middle and output) SPPs waveguides, during our coupling and device scheme (see Figure 3(c)). From the Figure 3(c), we can easily obtain that the SPPs intensity of input SPPs waveguide can be completely transferred to output SPPs waveguide, via Stimulated Raman Adiabatic Passage (STIRAP) in the ideal case.

Figure 3. (a) The distance layout of the input, middle and output SPPs waveguide. These results show the gaps between input/output and middle SPPs waveguide. (b) The coupling strength of input (output) and middle SPPs waveguide $C_1$ ($C_2$) based on the distance layout. (c) The SPPs intensity evolution of input, middle and output SPPs waveguide.

Subsequently, we numerically demonstrate the robustness of our device with varying the geometrical parameters and plot the final transfer intensity of our device by varying the different geometrical parameters. In the Figure 4 (a), we plot the the final transfer intensity of output SPPs waveguide with varying the mismatching distance $\delta$ (from 0.1 m to 1 m), curve radius $R$ (from 20 m to 80 m) by fixing the minimum distance $d_{\text{min}} = 1$ mm, device length $L = 2$ m. Furthermore, we illustrate that our device is also robust to minimum distance $d_{\text{min}}$ and device length $L$, with fixing mismatching
distance $\delta = 500 \text{ mm}$ and curve radius $R = 50 \text{ m}$. From the result of Figure 4 (a) and (b), we can easily obtain that the final transfer intensity of output SPPs waveguide reaches very close to 1 with different combination of all the geometrical parameters. Therefore, we can claim that our designed device is robust to all the geometrical parameters, including the mismatching distance $\delta$, curve radius $R$, minimum distance $d_{\text{min}}$ and device length $L$.

Figure 4. The robustness of our device with against all geometrical parameters. (a) The final transfer intensity of output SPPs waveguide with with varying the mismatching distance $\delta$, the curve radius $R$ and by fixing the minimum distance $d_{\text{min}} = 1 \text{ mm}$, device length $L = 2 \text{ m}$. (b) The final transfer intensity of output SPPs waveguide with with varying the minimum distance $d_{\text{min}}$, device length $L$ and by fixing the mismatching distance $\delta = 0.5 \text{ m}$ and the curve radius $R = 50 \text{ m}$.

4. Conclusions

In this paper, we propose a novel robust and broadband design of SPPs waveguide coupler, to completely transfer intensity of SPPs from input to output SPPs waveguide under the frequency range of microwave by employing Stimulated Raman Adiabatic Passage (STIRAP). The robust and broadband of our device comes from STIRAP. The features of robust and broadband are also demonstrated in ref. [14] and [15]. Based on the theory of STIRAP, the only condition of coupling strength between input (output) and middle SPPs waveguide $C_1$ ($C_2$) is that, at the beginning, $C_2$ should be much larger than $C_1$. At the end of device, $C_1$ should be much smaller than $C_2$ [6]. Therefore, the shape of coupling strength between input (output) and middle SPPs waveguide can be had larger disturbance. Due to the one-to-one mapping between the coupling strength and geometrical parameters, our device has a good ability to suffer the errors of the geometrical parameters.

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