Adiabatic following of terahertz surface plasmon-polaritons coupler via two waveguides structure

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Most recently, two remarkable papers [New J. Phys. 21, 113004 (2019); IEEE J. Sel. Top. Quantum Electron 27, 1 (2020)] propose broadband complete transfer terahertz (THz) surface plasmon-polaritons (SPPs) waveguide coupler by applying coherent quantum control - Stimulated Raman adiabatic passage (STIRAP). However, previous researches request three SPPs waveguides coupler. In this paper, we propose a new design of a broadband complete transfer THz SPPs coupler with an innovative structure of two waveguides by employing two state adiabatic following. In order to realize this design, we introduce the detuning parameter into the coupling equation of SPPs waveguides for the first time. We believe that this finding will improve the THz communication domain.

I. INTRODUCTION

Terahertz (THz) surface plasmon-polaritons (SPPs) waveguide coupler is the critical element device for THz communication [2, 3, 6] and detection [4]. The conventional THz SPPs coupler device [5–11] is made of two parallel coupling of SPPs waveguides and the disadvantages of those designs are that they only can operate at one single working frequency and the performance is very sensitive to geometric parameters. To solve those problems, most recently, we propose the broadband and robust complete transfer of THz SPPs waveguide coupler by employing coherent quantum control, named Stimulated-Raman-adiabatic-passage (STIRAP) [12, 13]. The coherent quantum control is a very robust method for the quantum system [18, 19] and currently, it is widely used in many classical systems, such as broadband optical waveguide coupler [20–22], nonlinear optics [23] and wireless energy transfer [24, 25].

The idea of the THz SPPs coupler device based on STIRAP is established by three special curve SPPs waveguides, which forces the coupling strengths of each two adjacent SPPs waveguides with satisfying STIRAP [12, 13]. However, those designs require three SPPs waveguides coupler and it brings complex fabrication process. In this paper, we propose a broadband complete transfer device with two SPPs waveguides coupler, which is realized by two-state adiabatic following.

The two-state adiabatic following is a well-known coherent quantum control technique, which requires tuning the coupling strength and detuning of the coupled equation. We have already well studied the coupling strength in the coupled equation of SPPs waveguides coupler [12, 13]. However, the detuning of the coupled equation is still an open problem and most recently, a remarkable paper demonstrates that the different width of SPPs waveguide can confine different prorogation constant of SPPs waveguide [14]. Based on this idea, we introduce the detuning parameter into the coupled equation of THz SPPs waveguides for the first time in this paper. Therefore, we build up a complete Schrodinger equation for SPPs waveguides coupled equation. Subsequently, we can tune the geometrical parameters of the SPPs waveguides coupler to satisfy the coupling strength and detuning of the two-state adiabatic following. In this configuration, we can obtain the broadband complete transfer of THz SPPs waveguides coupler, as shown in Fig. 1.

In this paper, we first introduce the detuning parameter of SPPs waveguides coupled equation and obtain the relationship between the geometrical parameter of SPPs waveguide and detuning parameter. Based on this finding, we can easily design the two SPPs waveguide coupler to achieve the broadband complete transfer device. In the section III, we run the numerical calculation of the coupled equation to demonstrate the complete transfer of SPPs energy. Besides, we use the full-wave simulation of our device with different frequencies of input THz waves to illustrate the broadband feature of our device.

FIG. 1. The schematic figure of our broadband device with two SPPs waveguides coupling.
II. ADIABATIC FOLLOWING OF SPPS WAVEGUIDES COUPLER

It has already proofed that the coupled equation of SPPs waveguides is equivalent to Schrodinger equation \[27, 28\], as written as,

\[
i \frac{d}{dz} \begin{bmatrix} c_1(z) \\ c_2(z) \end{bmatrix} = \begin{bmatrix} \beta_1(z) & \Omega(z) \\ \Omega(z) & -\Delta(z) \end{bmatrix} \begin{bmatrix} c_1(z) \\ c_2(z) \end{bmatrix}, \tag{1}\]

where \(c_1\) and \(c_2\) are the amplitudes of SPPs energy with respective to input and output SPPS waveguides. \(\beta_1\) and \(\beta_2\) are the propagation constants of input and output SPPs waveguides. \(\Omega\) is the coupling strength between input and output SPPs waveguides. It is straightforward to obtain the detuning parameter \(\Delta\), such as,

\[
i \frac{d}{dz} \begin{bmatrix} c_1(z) \\ c_2(z) \end{bmatrix} = \begin{bmatrix} \Delta(z) & \Omega(z) \\ \Omega(z) & -\Delta(z) \end{bmatrix} \begin{bmatrix} c_1(z) \\ c_2(z) \end{bmatrix}, \tag{2}\]

where the detuning \(\Delta(z) = \frac{\beta_1(z) - \beta_2(z)}{2}\).

We now write Eq. 2 in the so-called adiabatic basis \[27, 28\] which is the eigenstates of the Hamiltonian,

\[
i \frac{d}{dz} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} -\sqrt{\Omega^2 + \Delta^2} & -i\hat{\vartheta} \\ -i\hat{\vartheta} & \sqrt{\Omega^2 + \Delta^2} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \tag{3}\]

where \(\tan 2\hat{\vartheta} = \frac{2\Delta}{\Omega}\). The connection between the amplitudes \(c_1\) and \(c_N\) and the adiabatic states \(a_1\) and \(a_2\) is given by

\[
a_1 = c_1 \cos \hat{\vartheta} - c_2 \sin \hat{\vartheta}, \tag{4a}\]
\[
a_2 = c_1 \sin \hat{\vartheta} + c_2 \cos \hat{\vartheta}. \tag{4b}\]

When the condition meets adiabatic condition \[27, 28\], shown as,

\[
|\hat{\vartheta}| \ll \left(\Omega^2 + \Delta^2\right)^{1/2}. \tag{5}\]

Mathematically, adiabatic evolution means that the non-diagonal terms in Eq. 3 are small compared to the diagonal terms and can be neglected. \(|a_1|^2\) and \(|a_2|^2\) remain constant \[27, 28\]. Then takes the explicit form

\[
\frac{2 \left(\Omega^2 + \Delta^2\right)^{3/2}}{|\Delta\hat{\vartheta} - \Omega\hat{\vartheta}|} \gg 1, \tag{6}\]

where \(\Omega\) and \(\Delta\) are derivative with \(z\) of \(\Omega\) and \(\Delta\). For our case the detuning \(\Delta\) change from some positive to some negative value, in this course the mixing angle \(\hat{\vartheta}\) changes from \(\pi/2\) to 0. With the SPPS energy initially in the input waveguide, the system stays adiabatically in state \(a_2\), so that the energy transfer to the output waveguide when \(\hat{\vartheta}\) approaches zero. We employ a typical configuration for coupling strength and detuning, which makes the Gaussian shape for coupling strength and linear shape for detuning.

III. DEVICE DESIGN

In order to tune the coupling strength and detuning, we obtain the relationship between geometrical parameters of SPPS waveguide and coupling strength (and detuning) in this section. In this paper, we use a periodical structure for THz SPPS waveguide \[15, 16\] with fixed \(h = 40\ \mu m\), \(a = 20\ \mu m\) and \(d = 50\ \mu m\), as shown in the small figure of Fig. 2. For the coupling strength, it is well-known about tuning the coupling strength \(\Omega(z)\) with changing distance between two SPPS waveguides, which has an exponential relationship with the distance between two SPPS waveguides \[12, 13\] based on the coupled mode theory (CMT).

For the detuning, we obtain that the width \(w\) of SPPS waveguide can remarkably tune the propagation constant \(\epsilon\) of the SPPS waveguide, as shown in Fig. 2. The blue line of Fig. 2 is the results based on the simulation of dispersion equation with varying the width \(w\) of SPPS waveguide. Our theory is based on the propagation constant on the plane metal, which is \(\beta = \frac{\omega}{c} \sqrt{\epsilon_d \epsilon_m} \tag{17}\), where \(\omega\) is the frequency of input THz wave and \(c\) is the light speed. \(\epsilon_d\) and \(\epsilon_m\) are the permittivities of substrate and metal. Then we can modify the propagation constant \(\beta\) with our structure,

\[
\beta = \frac{\omega}{c} \sqrt{\epsilon_d \epsilon_m'}, \tag{7}\]

where \(\epsilon_m'\) is the effective permittivity which can be controlled by the width \(w\) for \(\epsilon_m' = A |d-a|e^{\omega w+(a-w)h}|c_m+|h|\epsilon_d|, \) where \(A\) is the fitting number as shown in red line of Fig. 2.

From the result of Fig. 2, thus we vary the width \(w\) of SPPS waveguide to control the detuning \(\Delta(z)\). Based on the adiabatic following theory and tuning coupling...
strength $\Omega(z)$ and detuning $\Delta(z)$, we can give an example of set of detuning $\Omega(z)$ and $\Delta(z)$, given as

$$\begin{align*}
\Omega(z) &= \Omega_0 \exp\left(-\left(\frac{z^2}{b^2}\right)\right); \\
\Delta(z) &= \frac{2\Delta_0 z}{-L},
\end{align*}$$

(8)

where $\Omega_0$ is the maximum coupling strength with minimum distance between two SPPs waveguides and $\Delta_0$ is maximum detuning based on the difference between the minimum and maximum width of SPPs waveguide. We take the parameters $b = 200 \text{ \mu m}$ and $L$ is the length of our device from -500 $\mu m$ to 500 $\mu m$. The functions of coupling strength and detuning are shown in Fig. 3(a).

Therefore, we vary the distance between two SPPs waveguide to change the coupling strength $\Omega(z)$ (see the red line of Fig. 3(b)) and vary the width of input SPPs waveguide to change the detuning $\Delta(z)$ (see the blue line of Fig. 3(b)). In this configuration of the distance of two SPPs waveguides and the width of the input SPPs waveguide, the coupling strength and detuning satisfy the adiabatic following (Fig. 3(a)). Therefore, we run the numerical calculation of Eq. 2 with the functions of coupling strength $\Omega(z)$ and detuning $\Delta(z)$, as shown in Fig. 3(c). From the result, it is very easy to find that the SPPs energy can complete flow from input to output SPPs waveguide.

IV. FULL-WAVE SIMULATIONS

Due to the complex boundary condition of SPPs waveguides, it is very tough to analytically and numerically calculate the evolution of SPPs energy based on Eq. 2. Therefore, in order to demonstrate the broadband feature of our device, we employ the full-wave simulations of our device with different input THz waves but keeping the same structure of our device from 0.6 THz to 0.9 THz, as shown in Fig. 4. As we can see from the results (Fig. 4), our device has very good performance with different input THz waves. Indeed, in order to change the detuning $\Delta(z)$ of our device, we should vary the width of the input SPPs waveguide. It indeed brings some perturbations of SPPs energy with spreading the whole width of SPPs waveguide, which leads some SPPs energy on upper input SPPs waveguide not to couple and transfer to output SPPs waveguide. This is the reason why some energy of SPPs still remains within the input SPPs waveguide. However, based on our full-wave simulations, our device can perform relatively good performance with complete transfer SPPs energy from input to output SPPs waveguide.

V. CONCLUSION

In this paper, we obtain the detuning parameter of SPPs waveguides coupled equation which is built up a full model for two-level quantum system for the first time. By tuning the detuning and coupling strength via the geometrical parameters of our device, we propose a broadband and complete transfer two SPPs waveguide coupler by employing two-state adiabatic following. Our device not only can maintain the broadband feature, but also reduce the fabrication complexity and cost. We believer that this finding will improve the research domain in THz communication and THz imaging.
FIG. 4. The full-wave simulations of our device with input THz wave frequencies.

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