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Femtosecond surface plasmon pulse propagation with the balance between group velocity dispersion and loss dispersion in a superlattice

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ABSTRACT

Due to strong dispersion of metal, the short pulse will broaden inevitably when it propagates in surface plasmon polariton (SPP) waveguide. In order to overcome this problem, we analyze effect of loss dispersion near loss peak and valley on pulse width. SPP superlattice is proposed to realize balance between the GVD and loss dispersion. The GVD and loss dispersion are determined by structure parameters of superlattice. Therefore, the balance between GVD and loss dispersion can be realized for pulse with center wavelength of 1550 nm by altering structure parameters. The width of output pulse will not alter after it travels through the superlattice. This structure offers another way to realize pulse width unchanged by balance between GVD and loss dispersion for femtosecond pulse at given center wavelength.

1. Introduction

The surface plasmon polaritons (SPPs) are regarded as potential information carriers of next generation integrated photonic circuit due to the ability of overcoming the diffraction limit of light [1–3]. SPPs can be used for engineering nanoscale photonic circuits operating at optical frequencies [4]. Plasmonic circuits may merge the fields of photonics and electronics at the nanoscale [5], so as to overcome the existing difficulties related to the large size mismatch between the micrometre-scale bulky components of photonics and the nanometre scale electronic chips. Thus, this research field is attracting great interest in recent years also as a consequence of the observation of new phenomena (plasmarons [6,7], acoustic surface plasmon [8,9]) and of the promising prospect of innovative THz plasmonic devices [5,10,11]. In particular, femtosecond SPP pulse propagation has attracted extensive research interest [3,12–15]. However, pulse will broaden inevitably when the short pulse propagates in the plasmonic waveguide due to the group velocity dispersion (GVD) of the metal [12,16–18]. This will limit the propagation distance, data rates and storage capacity [19].

Soliton is formed through the balance between self-phase modulation and GVD. It is a method of counteracting GVD-induced pulse broadening by the self-phase modulation. Soliton plasmonic phenomenon has been discussed in the single metal–dielectric interface [20,21], the metal slab bounded by dielectric, the dielectric slab bounded by metal [22] and insulator–insulator–metal waveguide [19].

Loss dispersion (LD) effects can substantially modify pulse duration (broadening/narrowing) when femtosecond SPP propagates in metal/insulator waveguide [12]. The balance between GVD- and LD-induced effects was seen, with adjacent bands of temporal pulse narrowing and broadening in the vicinity of metal's interband loss resonance. However, it was found that SPP pulse at 1550 nm would suffer substantial broadening [12]. The reason for LD effects on pulse width remains unclear in Ref. [12]. Here we analyze the reason for effects of LD on pulse width, then propose a SPP superlattice to realize balance between the GVD and LD. The GVD and LD are determined by structure parameters of superlattice. Therefore, the balance between GVD and LD can be realized for pulse with given center wavelength by altering structure parameters. For the femtosecond pulse with center wavelength 1550 nm, the width of output pulse will not alter after it travels through the superlattice.

The paper is organized as follows. Section 2 discusses the effects of LD on the pulse width. In Section 3, a SPP superlattice is proposed. The effects of GVD and LD on pulse width are discussed. Moreover, the GVD can be counteracted by LD through selecting the suitable structure parameters of the superlattice. After the femtosecond pulse with center wavelength 1550 nm propagates through superlattice, the output pulse width does not

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change compared with the input pulse width. Finally, conclusions are presented in Section 4.

2. Effect of LD on pulse width

We suppose that Gaussian profile SPP pulse propagates along x-axis in a SPP waveguide (shown in Fig. 1(a)). At the input terminal of the waveguide (suppose that $x=0$), the pulse in time domain can be expressed as

$$f(0,t) = \exp(-i\omega_0 t)\exp(-t^2/\tau_0^2) \quad (1)$$

where ω_0 is center angular frequency of the pulse and τ_0 is the $1/e$ half-width. Transforming Eq. (1) by the Fourier method, we obtain the frequency spectrum of input pulse

$$F(0,\omega) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty} f(0,t)\exp(i\omega t)\mathrm{d}t. \quad (2)$$

Suppose that $k(\omega) = k_1(\omega) + ik_2(\omega)$ is the effective wave vector of the SPP waveguide. Here, $k_1(\omega)$and $k_2(\omega)$ are the real part and imaginary part of complex wave vector $k(\omega)$, respectively. $k_1(\omega)$ represents GVD, and $k_2(\omega)$ describes LD. Multiplying Eq. (2) by the factor $\exp[ik(\omega)x]$, we obtain the frequency spectrum $F(x,\omega)$ of output pulse. The modulus of $F(x,\omega)$ is represented as

$$|F(x,\omega)| = (\tau_0/\sqrt{2})\exp[-(\omega-\omega_0)^2/\Delta\omega^2]\exp[-k_2(\omega)x] \quad (3)$$

where $\Delta\omega$ is the $1/e$ half-width of the spectrum. According to Eq. (3), the LD will change frequency spectrum when the pulse propagates in the waveguide. $k_2(\omega)$ is expanded into second-order Taylor series at the frequency ω_0

$$k_2(\omega) \approx k_2(\omega_0) + k_2'(\omega_0)(\omega-\omega_0) + \frac{1}{2}k_2''(\omega_0)(\omega-\omega_0)^2 \quad (4)$$

where $k_2'(\omega)$ and $k_2'(\omega)$ are first-order derivative and second-derivative, respectively. In order to analyze pulse width effected by LD near the loss peak and valley of waveguide, we suppose that $k_2'(\omega) = 0$. Eq. (4) is written as

$$k_2(\omega) \approx k_2(\omega_0) + k_2''(\omega_0)(\omega-\omega_0)^2. \quad (5)$$

Substituting Eq. (5) into Eq. (3)

$$|F(x,\omega)| \approx (\tau_0/\sqrt{2})\exp\left[-(\omega-\omega_0)^2/\Delta\omega^2\right]\exp\left\{-\left[k_2(\omega_0) + \frac{1}{2}k_2''(\omega_0)(\omega-\omega_0)^2\right]x\right\}. \quad (6)$$

When the center frequency ω_0 of pulse is equal to the frequency corresponding to loss peak in Fig. 1(c), $k_2''(\omega_0) < 0$, $k_2(\omega_0) > k_2(\omega_1)$ and $k_2(\omega_0) > k_2(\omega_2)$ (ω_1 and ω_2 are the frequencies at $1/e$ amplitude in Fig. 1(b)). According to the Eq. (6), the loss at frequency ω_0 is larger than the loss at frequencies ω_1 and ω_2. The normalized frequency spectrum width of pulse will increase, and the corresponding pulse width in the time domain will decrease. Therefore, the pulse width in time domain will decrease due to the LD when the center frequency of pulse is near loss peak frequency. On the contrary, the pulse width in time domain will increase due to the LD when the center frequency of pulse is near the frequency corresponding to loss valley shown in Fig. 1(d). Therefore, we can design a waveguide, whose LD curve has a loss peak, to counteract GVD-induced pulse broadening by LD-induced pulse narrowing. Pulse width may be unchanged after pulse with center wavelength near loss peak frequency propagates through this waveguide.

3. The balance between GVD and LD dispersion of superlattice

3.1. Structure design

The schematic diagram of superlattice discussed in this paper is shown in Fig. 2. The core layer is air and the metal layer is silver. The whole waveguide can be represented by $(AB)^N$, where A and B are metal–insulator–metal (MIM) waveguide with insulator widths w_A and w_B in the transverse y direction, respectively. N denotes period number of AB part. The length of A and B parts are l_A and l_B,

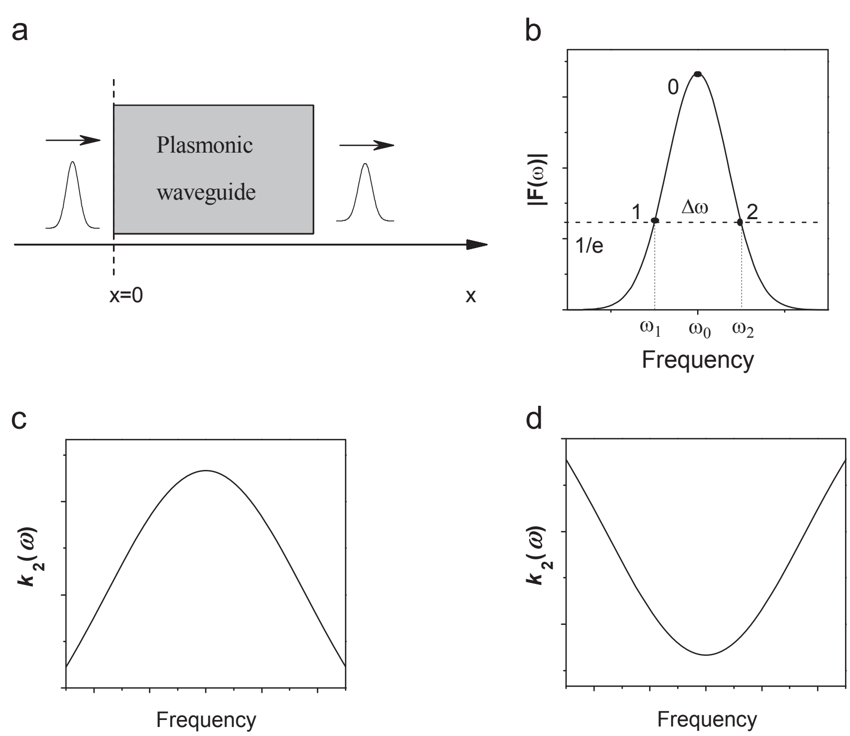

Fig. 1. (a) Scheme of the waveguide. (b) Frequency spectrum of the Gaussian pulse. ω_0 is center frequency of the pulse, ω_1 and ω_2 are frequencies at $1/e$ amplitude. (c) The LD curve with a loss peak. (d) The LD curve with a loss valley.