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Optical amplification using surface plasmon resonance with total internal reflection

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ABSTRACT

The surface plasmon enhanced optical amplification is proposed, designed and simulated in Kretschmann geometry formed by a 500 μm thick, 10 mm long and 5 mm wide BK_7 parallel slab and 29 nm thin gold layer which is sandwiched between the said parallel slab and 20 nm thin GaAs layer. This GaAs layer is pumped by 1319 nm higher order Gaussian beam of a Nd:YAG laser, which passes through a cylindrical lens thereby generating a high aspect ratio elliptical cross section to attain intensity dependent negative extinction coefficient on that 3 mm long strip of irradiated GaAs. The negative extinction coefficient of GaAs layer facilitates the amplification of the incident optical radiation at 1550 nm within the communication window. Here the incident pulsed optical radiation of 5 mW is amplified to 274 MW through external pumping and surface plasmon resonance phenomenon by total internal reflection with three bounces along the length of said BK_7 parallel slab considering the Goos–Hänchen shift at the slab-Au layer interface and slab-air interface.

1. Introduction

Surface plasmon (SP) is an electromagnetic wave propagating along the interface of metal-dielectric and highly sensitive to any change of this boundary [1]. Creation of SP will only be possible when a *p*-polarized light of a particular wavelength with required angle of incidence is directed through an optical component and reflected from a metal film deposited on the optical component facet [1]. Under optimal condition, a large portion of optical energy is converted into a guided electromagnetic wave along the interface of the metal-dielectric where optically excited SP is quite strong [2]. This SP phenomenon was first observed by Wood [3], theoretically investigated by Zenneck [4], its existence was predicted by Ritchie [5] and experimentally demonstrated by Otto [6], Kretschmann [7] and Raether [8]. In the presence of surface plasmon resonance (SPR) there will be a sharp rise in electric field of incident radiation at the interface gaining the energy from plasmon wave, which is termed as Electric Field Enhancement Effect (EFEE), where the output light intensity is several times greater than the incident light intensity [9–12]. In this way amplification of the incident radiation can be possible through SPR whereas the amplification with surface plasmon resonance in semiconductor sub-wavelength waveguide devices by high current injection has already been observed by J.B. Khurgin et al. in 2012 [13].

2. Proposed scheme

The proposed configuration in Fig. 1 is used to provide the SP enhanced optical amplification resulting from an excitation of SPR in the gold–GaAs interface by a TM-polarized incident laser radiation for a free space wavelength of 1550 nm at 26 °C temperature. In Fig. 1 the Kretschmann geometry is formed by a BK_7 parallel slab, 29 nm thin gold (Au) layer ($n = 0.38 + 10.75i$) and 20 nm thin GaAs ($n = 3.377$) layer where the gold layer is sandwiched between the BK_7 parallel slab and GaAs layer. Here the BK_7 parallel slab is 10 mm long, 5 mm wide and 0.5 mm thick. This parallel slab is having refractive index (n) 1.50066 with extinction coefficient (k) zero for a free space wavelength of 1550 nm at 26 °C temperature [14,15]. In Fig. 1 an external pumping by 1319 nm Nd:YAG laser transform the extinction coefficient value of GaAs layer from marginal positive to negative [16,17]. Using a cylindrical lens having radius 2 mm, focal length 3.9 mm, height 4 mm and length 6 mm a higher order Gaussian beam of 1319 nm is converted to a high aspect ratio elliptical cross sectional beam at its focal length [18,19]. The beam spot size through the cylindrical lens with TM_{00} mode has been calculated by [20].

$$Spot\ size = \frac{4M^2\lambda f}{\pi D} \quad (1)$$

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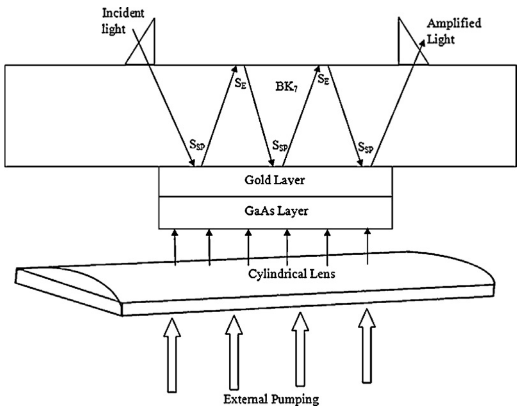

Fig. 1. Surface plasmon enhanced optical amplifier with BK_7 parallel slab.

where λ is the incident wavelength, f is the lens focal length, D is the input beam diameter onto the lens and M^2 is the input laser mode. In Fig. 1 the proposed source of the fundamental comes from an tunable laser operating at a center wavelength of 1550 nm is pulse modulated at a repetition frequency of 1 KHz, amplified by an erbium-doped fibre amplifier having 5 mW incident power with 4 mm^2 beam cross sectional area launched at the bottom surface of the parallel slab at a required angle of incidence for creating SP at metal-dielectric interface (for first bounce) [21]. This laser radiation encounters attenuated total internal reflection (ATR) at the parallel slab – gold layer interface [7]. ATR created evanescent wave when reaches at the gold–GaAs interface creates surface plasmon which further forms constructive interference with the evanescent wave resulting in SPR at the gold–GaAs interface. In this circumstances $k_{ep} = k_{sp}$ and mathematically expressed through [1,22].

$$k_{ep} = \frac{\omega}{c}\sqrt{\varepsilon_p}\sin\theta \tag{2}$$

$$K_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m \varepsilon_i}{\varepsilon_m + \varepsilon_i}} \tag{3}$$

where k_{ep} is the propagation constant of the evanescent wave, K_{sp} is the propagation constant of surface plasmon, ε_p is the dielectric constant of the BK_7, θ is the incident angle, ω is the frequency of the incident wave, c is the velocity of light in free space, ε_m and ε_i are the dielectric constants of the gold layer and GaAs layer respectively. In presence of the SPR wave and the external pumping wave the incident fundamental electric field experiences a sharp rise in amplitude which results in the amplification of the fundamental light intensity with the negative extinction coefficient of GaAs layer. Amplification of the incident light can be optimized for a 29 nm thin Au layer and it has been shown in Fig. 2 without considering the GaAs layer. As a result, the ATR signal spectrum at 29 nm thickness of the Au layer gives a sharp plasmon dip where the reflectivity R is 0 at an incident angle of 42.01°. Therefore the thickness of the Au layer is optimized at 29 nm where the excited SPR photon is maximum. Now we need to determine the thickness of the dielectric layer for which we need to consider the presence of GaAs layer in a non-excited state, having $n = 3.377 + 0.00013i$ at 26 °C temperature [16]. The simulated maximum SPR signal spectrum is obtained at 20 nm thickness of GaAs layer with an incident angle of 42.01° which is shown in Fig. 3. This 20 nm thin GaAs layer offers a low absorption loss with the extinction coefficient of 0.00013. The amplification of the incident optical radiation will only be possible if this extinction coefficient of the GaAs layer becomes negative under the influence of external pumping [23,24]. This can be mathematically expressed through the following formulae [25].

$$I_{out} = I_{in}\exp(-\alpha d) \tag{4}$$

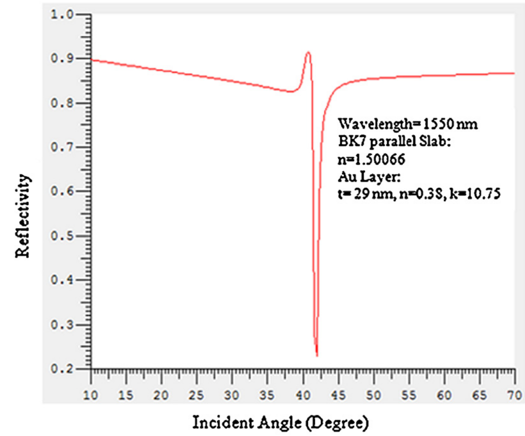

Fig. 2. Angle of incidence vs. reflectivity in absence of GaAs layer for optimizing the thickness of Au layer at 1550 nm wavelength.

$$\alpha = \frac{4\pi f' k'}{c} \tag{5}$$

$$\alpha(E) = \alpha_0\sqrt{\frac{E - E_g}{E_g}} \tag{6}$$

where I_{out} is the output light intensity, I_{in} input fundamental light intensity, α is the absorption coefficient, d is the path length, f' is the frequency of the incident light, k' is the extinction coefficient of the material, c is the velocity of light in free space, $\alpha(E)$ is the absorption coefficient as a function of E, α_0 is a constant having different numerical values for different materials, E is the amount of energy higher than the band gap energy, E_g is the band gap energy. The above equation clearly indicates that 20 nm thin GaAs layer for a pump power level of 3.1043 mW at a wavelength of 1319 nm steered through the cylindrical lens transforms the extinction coefficient of GaAs layer from marginal positive to negative. This optical pumping by pump laser creates a population inversion in the GaAs dielectric layer, which delivers adequate energy to excite the plasmon field further [23,24]. Here the pump source is a 1319 nm CW micro chip DPSS Nd:YAG laser, $E_g = 1.42$ eV and $\alpha_0 = 2.3 \times 10^4$/cm for 20 nm thin GaAs layer, which turns the extinction coefficient of GaAs layer from 0.00013 to −0.755534. The variation of amplified output with the variation of incident angle from this SPR configuration formed by BK_7 parallel slab coated with Au layer and optically pumped GaAs layer having negative extinction coefficient is shown in Fig. 4. The peak reflectivity of the order of 10^3 is found at 41.83°

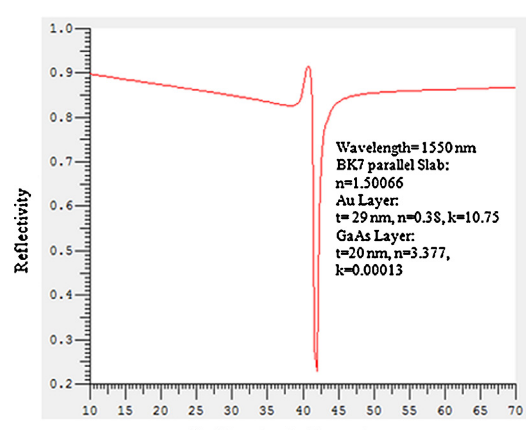

Fig. 3. Angle of incidence vs. reflectivity in presence of GaAs layer and Au layer with their optimum thicknesses at marginal +ve extinction coefficient of GaAs layer.