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Surface plasmon enhanced ultra-low threshold second harmonic generation in periodically poled whispering gallery resonator

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ABSTRACT

The surface plasmon enhanced ultra-low threshold second harmonic generation is observed, designed and simulated in whispering gallery resonator made of MgO doped periodically poled $LiNbO_3$. Here the electric field associated with incident optical radiation of picowatt level is amplified to milliwatt level through surface plasmon resonance in Kretschmann geometry which is formed by a BK_7 prism plane, 29 nm thin gold layer and 20 nm thin GaAs layer. This enhanced electric field then coupled to a whispering gallery resonator, which facilitated the generation of second harmonic for an incident laser radiation of picowatt level. In this proposed configuration with an incident optical power of 94.6 pW, generated second harmonic through whispering gallery resonator is found to be 14.6 mW.

1. Introduction

Surface plasmons are the electron density waves excited at the interface between metal and dielectric. Creation of surface plasmon wave will only be possible when a p-polarized light of a particular wavelength is directed through an optical component on metal-dielectric interface at a required angle of incidence [1]. Under optimal conditions, 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 [2]. The first observation of this surface plasmon phenomenon was reported by Wood [3] where an unexpected narrow dark band in the spectrum has been formed in presence of the metallic grating which is considered to study the diffraction of polychromatic light. After that, the theoretical investigation of the surface plasmon phenomenon was carried out by Zenneck [4] and the experimental research was manifested by Otto [5], Kretschmann [6] and Raether [7]. At surface plasmon resonance (SPR) condition the amplitude of the plasmon field is maximum resulting minimum intensity after reflection that even attains zero value. But in off-resonance condition the output light intensity may be several tens of times of the incident light intensity by this electric field enhancement effect [2]. Thus, amplification of the incident radiation can be envisioned through surface plasmon resonance (SPR).

On the other hand, whispering gallery resonator (WGR) based on total internal reflection has attracted much attention in the field of optical physics and device applications because of their high quality factor [8]. Basically the structure of whispering gallery may be a circular, elliptical or ellipsoidal micro-cavity [9]. In these types of micro-cavities, light ray inside the medium can experience total internal reflection at a particular angle of incidence. If the medium has a circular shape, such as a circular disk, certain number of frequencies experience many total internal reflections and constructively interferes after a complete roundtrip, which is known as WGR [10]. Light ray continues to resonate around the edge of the periodically poled circumferential area of WGR, resulting in increase in the cavity's Q-factor. If the edge of this WGR is periodically poled for second harmonic generation (SHG), second harmonic of incident radiation can be achieved at a required angle of incidence at prism-WGR interface. With a high Q-factor of WGR our proposed scheme first time predicts the generation of second harmonic at a threshold power of picowatt level, in contrast with the lowest reported threshold power for SHG at milliwatt level [11].

2. Proposed scheme

The proposed configuration in Fig. 1 is used to provide SHG in periodically poled WGR with Kretschmann geometry using a BK_7

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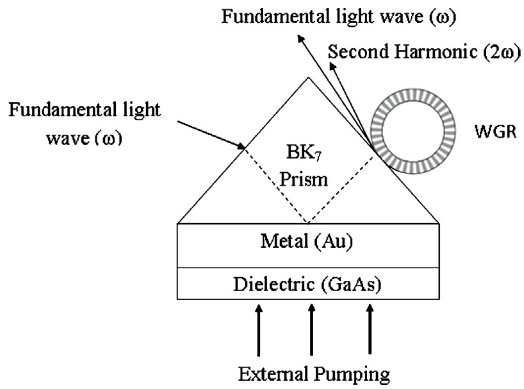

Fig. 1. Reflected second harmonic generation through WGR: BK_7 prism (n = 1.50066); thin gold layer (t = 29 nm, n = 0.38 + 10.75i) and GaAs dielectric layer (t = 20 nm, n = 3.377 – 0.75534i).

prism. In Fig. 1 an optical amplifier is formed by a right angle prism (n = 1.50066) with base length 15 mm and width 10 mm, a 29 nm thin gold (Au) layer (n = 0.38 + 10.75i) and a 20 nm thin GaAs layer (n = 3.377), where the gold layer is sandwiched between the incident plane of prism and GaAs layer at a free space wavelength of 1550 nm with 26 °C temperature. In Fig. 1 an external pumping through 1319 nm CW microchip DPSS laser is used to convert the extinction coefficient of GaAs layer from positive to negative.

Here the proposed source of the fundamental comes from an external cavity tunable laser operating at wavelength of 1550 nm is pulse modulated at a repetition frequency of 1 kHz, amplified by an erbium-doped fiber amplifier and launched into the Bk_7 prism at a required angle of incidence [12]. This laser radiation encounters attenuated total internal reflection (ATR) at prism–metal interface [13]. ATR created evanescent wave when reaches the metal–dielectric interface creates surface plasmon which further forms constructive interference with the evanescent wave resulting SPR at the metal–dielectric interface. In this situation $k_{ep} = K_{sp}$ and mathematically expressed through [1,14].

$$k_{ep} = \frac{\omega}{c}\sqrt{\varepsilon_p}\,\sin\theta \tag{1}$$

$$K_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_m\varepsilon_i}{\varepsilon_m+\varepsilon_i}} \tag{2}$$

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 on the prism-metal interface, ω is the frequency of the incident wave, c is the light velocity in free space, ε_m and ε_i are the dielectric constants of the metal and prism respectively. After the creation of surface plasmon resonance due to electric field enhancement effect and external pumping wave the incident electric field experiences a sharp rise which results in the amplification of incident light intensity at the output [15]. All the simulations are carried out by the simulation software Winspall (trademark) developed by Max Planck Institute and MATLAB.

Amplification of the incident light can be optimized for a 29 nm thin Au layer and it has been shown in Fig. 2, for Bk_7 Prism: n = 1.50066; for Au layer: n = 0.38 + 10.75i at 26 °C [16,17] 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 40.56°. Therefore, the thickness of 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 this purpose we have considered that the GaAs layer is present in a non-excited state, having n = 3.377 + 0.00013i at 26 °C [15]. The simulated maximum SPR signal spectrum is obtained at

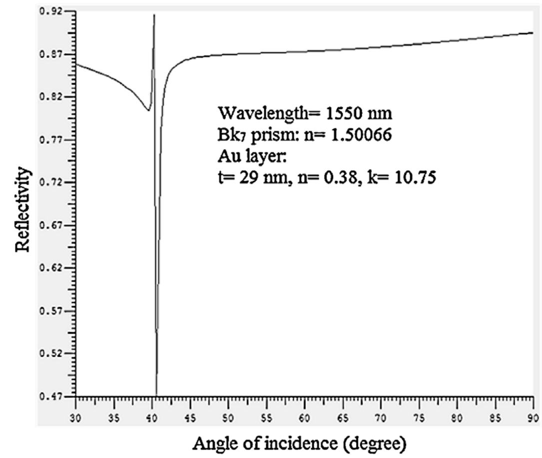

Fig. 2. Angle of incidence vs reflectivity.

20 nm thickness of GaAs layer with an incident angle of 41.79° which is given in Fig. 3.With this 20 nm thickness of GaAs layer a little beat absorption loss is observed with the extinction coefficient of 0.00013. The amplification of the incident optical radiation will only be possible if the extinction coefficient of the GaAs layer becomes negative. In these circumstances the mathematical formulae for the extinction coefficient can be depicted by [18–20].

$$I_{out} = I_{in}\exp(-\alpha d) \tag{3}$$

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

$$\alpha(E) = \alpha_0\sqrt{\frac{E-E_g}{E_g}} \tag{5}$$

where I_{out} is the output light intensity, I_{in} input fundamental light intensity, α is the absorption coefficient of the material, d is the path length, f' is the frequency of the incident light, k' is the extinction coefficient of the material, c is the light velocity in free space, $\alpha(E)$ is the absorption coefficient as a function of E, α_0 is a constant having numerical value for different materials, E is the energy higher than the band gap energy, E_g is the band gap energy. The above equation clearly indicates that the 20 nm thin GaAs layer with appropriate power level of 3.1043 mW for a pump wavelength of 1319 nm through lens transforms the extinction coefficient of GaAs layer from marginal positive to negative. Optical pumping by pump laser creates a population inversion in the GaAs dielectric layer, which delivers adequate energy to excite the plasmon field further [21,22]. Here the pump source is a 1319 nm CW microchip

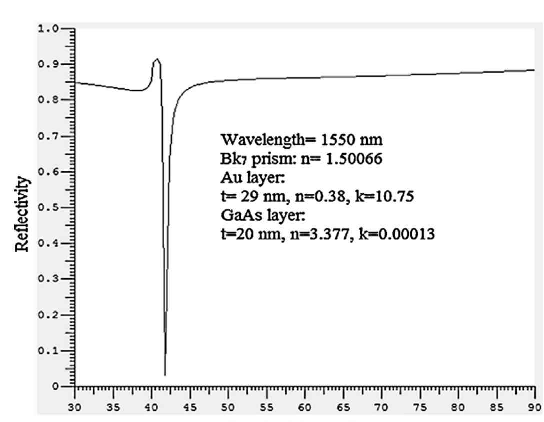

Fig. 3. Angle of incidence vs reflectivity.