Optics Communications 367 (2016) 86–94

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Invited Paper

Analysis of waveguide-coupled directional emission for efficient collection of Fluorescence/Raman light from surface

Chen Chen, Dan-Feng Lu, Ran Gao, Zhi-Mei Qi*

State Key Laboratory of Transducer Technology, Institute of Electronics, Chinese Academy of Sciences, Beijing 100190, P.R. China

ARTICLE INFO

Article history:
Received 27 August 2015
Received in revised form
21 December 2015
Accepted 1 January 2016
Available online 4 February 2016

Keywords:
Plasmon waveguide
Resonant mirror
Directional emission

ABSTRACT

A theoretical method based on the optical reciprocity theorem combined with the Fresnel theory has been developed for the analysis of waveguide-coupled directional emission technique, which is useful for the surface Fluorescence/Raman spectroscopy. The Kretschmann-type waveguide with a molecular dipole located above or inside the core layer serves as the simulation model. The two-dimensional (2D) pattern of power density for the waveguide-coupled emission from the molecular dipole was calculated using the theoretical method. According to the results, with a given waveguide the 2D pattern of power density is highly dependent on both the orientation and position of the dipole. The maximum fraction of power occupied by the waveguide-coupled emission is 87% with the plasmon waveguide and 95% with the resonant mirror. Compared with the dipole emission in free space, the waveguide-coupled directional emission possesses easy collection, which is benefit for the detection of weak Fluorescence and Raman signals. From this point, the theoretical method used here is helpful for design and optimization of Kretschmann-type waveguide structures for high-sensitivity surface monitoring by Fluorescence/Raman spectroscopy.

Fluorescence and Raman spectroscopies are two important analytical techniques with widespread applications in the fields of chemistry and biochemistry [1–4]. One way to improve their sensitivities is generation of high-quality resonance modes with layered structural substrates. In specific, two main advantages can be obtained by using this kind of substrates. In the process of excitation, the intensity of Fluorescence/Raman signals can be improved through the enhancement of local electric field. The enhancement factor is one of the most important factors in the design of surface enhanced Fluorescence/Raman substrates, such as gold nanoparticles and nanorods [5–7]. In the process of radiation, the radiation pattern of Fluorescence/Raman signals in free space can also be modified for the high-efficiency collection. It has been reported that only about 1% of the radiation power can be collected with conventional detection method [8–10]. This extremely low collection efficiency indicates that the Fluorescence/Raman sensitivity can be considerably improved in the absence of a larger local electric field, which may destroy the target molecules in some cases. However, the problem of low collection efficiency has not attracted enough attention.

Kretschman-type waveguides, including plasmon waveguide and resonant mirror, have been introduced to the field of Raman spectroscopy owing to several outstanding features, which can overcome the drawbacks of conventional SERS substrates [11,12]. Firstly, the field enhancement factors can be precisely predicted and controlled, which enables us to manipulate the Raman sensitivity with high repeatability. Secondly, by using the transverse electric (TE) and transverse magnetic (TM) modes, the orientation of molecules immobilized on the waveguide surface can be estimated. Thirdly, the undesirable impact of noble metals on the Raman spectra of target molecules can be avoided upon the use of dielectric waveguide. In the previous work of our group, the guided-mode-coupled directional emission property of plasmon waveguide and resonant mirror has been reported [13]. The radiation power from a molecular dipole located above or inside the core layer of a plasmon waveguide or a resonant mirror can be efficiently coupled into the resonance modes to be emitted into the prism at the corresponding resonance angles. However, only one-dimensional power density distribution has been provided which is not sufficient to study the power fraction that enters the prism. In this work, two-dimensional power density from a molecular dipole located in the mode-field occupying space (above, on the surface, and inside the core layer of a waveguide) are calculated for a comprehensive understanding of the waveguide-coupled directional emission technique.

* Corresponding author.
E-mail address: zhimei-qi@mail.ie.ac.cn (Z.-M. Qi).

http://dx.doi.org/10.1016/j.optcom.2016.01.001

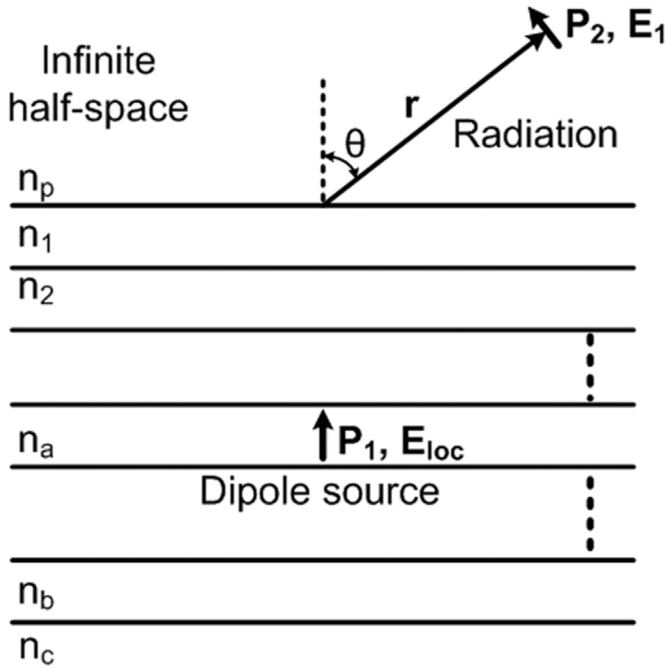

Fig. 1. Schematic diagram for explaining the optical reciprocity theorem applied to the layered structure (n_a represents refractive index of the a-th layer).

1. Basic theory

The optical reciprocity theorem states that the field $\mathbf{E_1}$ created at a given point Q_2 by a dipole $\mathbf{p_1}=p_1\mathbf{e_1}$ at point Q_1 is related to the field $\mathbf{E_2}$ created at point Q_1 by a dipole $\mathbf{p_2}=p_2\mathbf{e_2}$ at point Q_2 according to [14,15]:

$$\mathbf{P_1}\cdot\mathbf{E_2} = \mathbf{P_2}\cdot\mathbf{E_1} \quad (1)$$

Considering the distance between $\mathbf{p_1}$ and $\mathbf{p_2}$ (|$\mathbf{r}$|, $\mathbf{r}$ is a vector starts at Q_1 and ends at Q_2) is large enough, no scatterers are occurred between $\mathbf{p_1}$ and $\mathbf{p_2}$, and the orientation of $\mathbf{p_2}$ is parallel to the field $\mathbf{E_1}$ ($\mathbf{e_2}$ is perpendicular to $\mathbf{r}$), the field $\mathbf{E_2}$ can be approximated as a plane wave propagating along the direction opposite to $\mathbf{r}$:

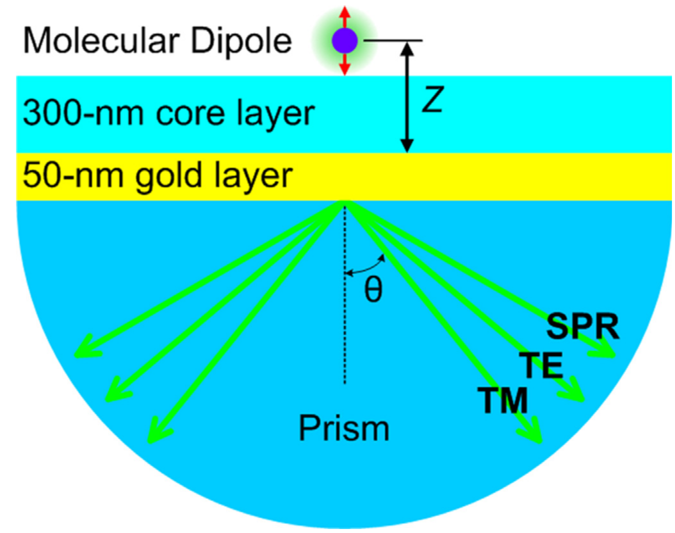

Fig. 3. Schematic diagram of the Kretschmann-type plasmon waveguide used for simulation.

$$\mathbf{E_2} = E_p\mathbf{e_2} = \frac{\omega^2 p_2 e^{ikr}}{4\pi\varepsilon_0 c^2|\mathbf{r}|}\mathbf{e_2} \quad (2)$$

E_p is the amplitude of the plane wave and k is the wave vector.

When the dipole $\mathbf{p_1}$ is located in a layered structure, $\mathbf{E_2}$ is no longer a plane wave and it can be replaced by the local field ($\mathbf{E_{loc}}$) excited by the plane wave, as shown in Fig. 1. Substitution $\mathbf{E_2}$ into Eq. (1) with $\mathbf{E_{loc}}$ provides:

$$\mathbf{e_2}\cdot\mathbf{E_1} = \frac{p_1}{p_2}\mathbf{e_1}\cdot\mathbf{E_{loc}} = \frac{E_p}{p_2}p_1\frac{\mathbf{e_1}\cdot\mathbf{E_{loc}}}{E_p} = \frac{\omega^2 p_1 e^{ik_p r}}{4\pi\epsilon_0 c^2|\mathbf{r}|}\frac{\mathbf{e_1}\cdot\mathbf{E_{loc}}}{E_p} \quad (3)$$

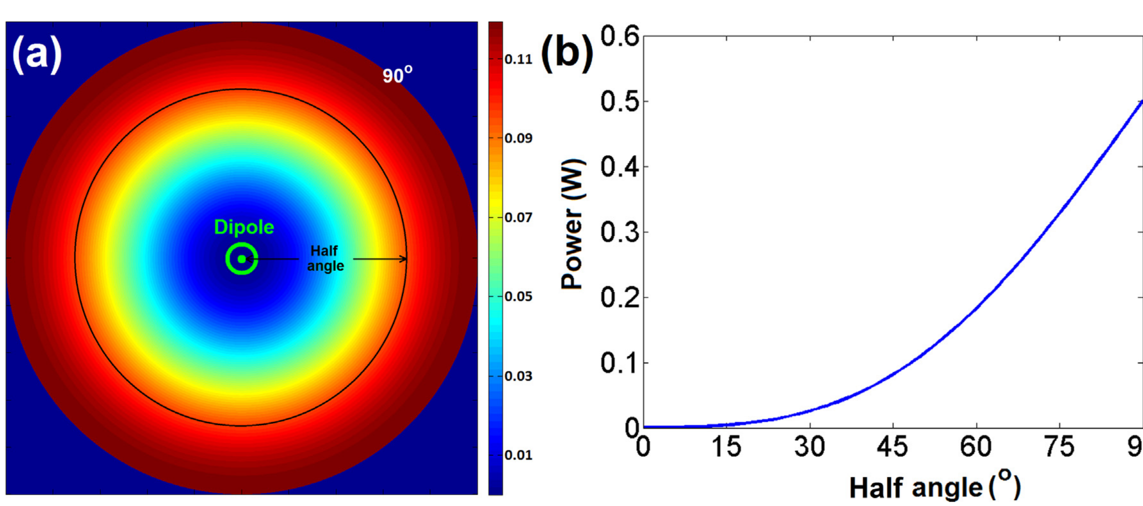

Fig. 2. (a) Two-dimensional power density distribution from a molecular dipole in free space. (b) Dependence of the maximum power on the half angle of the collection cone (the highest collection efficiency of 50% at the half angle of 90°).