Observation of Resonant Photon Tunneling in Photonic Double Barrier Structures

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Reflectance and transmittance of 632.8 nm He-Ne laser light for photonic double barrier structures (consisting of a SF10 prism, SiO₂ layer, Al or Al₂O₃ active layer, SiO₂ layer and SF10 prism) were measured as a function of the angle of incidence for both the p- and s-polarized incidence. Sharp reflection dips and transmission peaks were observed at angles larger than the critical angle of total reflection. The appearance of the transmission peaks can be attributed to resonant photon tunneling through the photonic double barrier structures analogous to resonant electron tunneling through double potential barrier structures. Resonant tunneling is mediated by the long-range surface plasmon polariton in the case of the Al active layer and the electromagnetic guided modes in the case of the Al₂O₃ layer.

Key words: resonant photon tunneling, frustrated total reflection, surface plasmon, guided mode, double barrier structure

1. Introduction

In recent years the analogy between the propagation of electromagnetic waves and that of electron waves has received much experimental and theoretical attention. The propagation of light in periodic dielectric structures, often referred to as photonic crystals, is currently the subject of intensive studies. The optical properties of photonic crystals can be discussed on the basis of the photonic band structure, which is the analogy of the electronic band structure in crystals. The existence of the photonic band gap leads to a variety of phenomena of both fundamental and practical interest. Another interesting analogy between photon and electron propagation, which has received less attention so far, lies in tunneling phenomena. This paper deals with photon tunneling, in particular, resonant photon tunneling.

Photon tunneling analogous to electron tunneling through a one-dimensional potential barrier (Fig. 1(a)) has been discussed by Chiao, Kwiat and Steinberg. They considered a simple structure of frustrated total internal reflection (FTIR) schematically shown in Fig. 1(b), in which two prisms having a high refractive index (n₁) are placed in close proximity across a sufficiently thin gap of a low refractive index (n₂) medium. When a light wave is incident on the first prism at an angle beyond the critical angle, an evanescent wave is generated inside the gap. Decoupling of the exponential tail of the evanescent wave into the second prism allows the transmission of light from the first prism to the second one through the gap. This phenomenon is closely analogous to electron tunneling through a potential barrier schematically shown in Fig. 1(a). By establishing an appropriate correspondence between quantities for photons (refractive index, angular frequency and angle of incidence) and those for electrons (energy, effective mass and height of potential barrier), the Helmholtz equation describing the photon propagation (for both the s- and p-polarized incidence) can be shown to be formally identical to the time-independent one-dimensional Schrödinger equation describing electron propagation. Briefly speaking, the variation of the potential height for electrons corresponds to that of refractive index for photons as schematically shown in Fig. 1(c). The variation of the energy of incident electrons corresponds to that of the energy or angle of incidence for photons.

In the case of electron tunneling through a double barrier structure as shown in Fig. 2(a), it is well known that the tunneling probability plotted as a function of the energy of incident electron exhibits a peak when the energy coincides with that of a quasi-bound state inside the potential well. This leads to so-called resonant electron tunneling. An analogous double barrier structure for photons is a FTIR structure shown in Fig. 2(b), in which a thin layer having a high refractive index (n₃) is inserted in the gap between the prisms. Hereafter, we call this type of FTIR structure photonic double barrier structure (PDBS). Resonant photon tunneling is expected to occur in the PDBS. About 50 years ago, an optical filter based on the PDBS was proposed and results of photon transmission experiments were reported by Turner. Otto calculated the transmittance of a PDBS containing an Ag thin film in a LiF gap and suggested the realization of a
(a) Electron tunneling through a single barrier

(b) Photon tunneling through a FTIR structure

(c) Variation of refractive index

Fig. 1. Schematic presentations of (a) electron tunneling through one-dimensional potential barrier, (b) frustrated total internal reflection geometry for photon and (c) variation of refractive index corresponding to that of electron potential.

More recently, Vigoureux and Baïda\(^9\) discussed the photon transmission through a multilayer system in terms of resonant photon tunneling. They considered a stratified medium made of dielectric layers of refractive indices of \(n_1\) and \(n_2\) \((n_2 < n_1)\) and theoretically analyzed a multilayer system constructed by an N-fold repetition of the \(n_1\)-\(n_2\)-\(n_1\) layer stack. The case of \(N=2\) corresponds to the PDBS shown in Figs. 2(b) and (c) with \(n_3 = n_1\). According to their results, when the wavelength is varied and the incident angle fixed, N-1 resonant transmission peaks appear. They predicted that for a small \(N\), the transmission peaks are extremely narrow and can hardly be observed experimentally, because unavoidable structural fluctuations such as the interface roughness may destroy the resonance condition. For \(N\) larger than about 40, on the other hand, the observation becomes feasible, since the resonant peaks are so close to one another that they form a wide transmission band. As far as the authors know, no experiment was performed to examine the prediction made by Vigoureux and Baïda; furthermore, in their paper, the mechanism of the resonance (identification of the resonant states for photons) was not discussed in detail. In view of recent growing interest in near-field optics, resonant photon tunneling, which is a consequence of specific properties of evanescent waves, may offer the possibility of various applications and deserve detailed studies.

The purposes of this paper are to demonstrate the feasibility of the resonant photon tunneling experiment in the PDBS and identify the mechanism of the resonance. We prepared PDBS containing an Al or Al\(_2\)O\(_3\) polarizer. Salwén and Stensland\(^8\) performed transmission experiments for the PDBS containing an Ag thin film. Although these previous studies are concerned with the photon transmission through the PDBS, the greatest interest centered around the fabrication of good optical filters and no attention has been given to the analogy between the observed or predicted phenomena and electron tunneling through double barrier structures.