Optics Communications 428 (2018) 191–199

Contents lists available at ScienceDirect

Optics Communications

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

Optical and quantum models of resonant optical tunneling effect

Aoqun Jian [a,b], Gang Bai [a,b], Yanxia Cui [b,c], Chongguang Wei [a,b], Xin Liu [b,c], Qianwu Zhang [d], Shengbo Sang [a,b,*], Xuming Zhang [e,**]

[a] MicroNano System Research Center, Taiyuan University of Technology, Taiyuan 03002, China
[b] Key Laboratory of Advanced Transducers and Intelligent Control System, Shanxi Province and Ministry of Education, Taiyuan 030024, China
[c] College of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan 030024, China
[d] Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Shanghai University, Shanghai 200072, China
[e] Department of Applied Physics, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong China

ARTICLE INFO

Keywords:
Optical tunneling
Total internal reflection
Resonant optical tunneling effect
Quantum optics

ABSTRACT

Resonant optical tunneling effect (ROTE) is a special phenomenon that light can fully go through the seemingly impenetrable optical structure. It is a prominent example to study the analogy of wave optics and quantum physics. Previous theoretical work mostly focused on the optical modeling of transmission spectrum using the transfer matrix method (TMM), but put little effort in the quantum model. This paper advances the optical modeling by using the finite-difference time-domain method (FDTD) to simulate the electric field distribution and by using the plane wave expansion (PWE) to predict the optical bandgap. Moreover, we present the first analytical quantum model of the ROTE and further derive a direct expression of the transmission peak positions. This expression cannot be derived by the optical models, but its predicted peak positions match the optical modeling results using the FDTD, the PWE and the TMM. This well demonstrates the merit of the quantum analogy for analyzing the optical systems. This work may inspire the transplantation of the established ideas and designs in the quantum field into the optical field to create new optical and photonic devices.

1. Introduction

Photonic tunneling, which represents a special phenomenon that lightwave can tunnel through classically impenetrable optical structures, has been a key topic of intense scrutiny over decades [1–5]. As a unique effect combining both the photonic tunneling and the resonance phenomenon, resonant optical tunneling effect (ROTE) has attracted extensive theoretical [6–13] and experimental [14–20] studies in recent years. As shown in Fig. 1, the ROTE structure basically consists of 5 layers with a high–low–high–low–high distribution of refractive index (RI). A special feature of ROTE is that the incident angle θ is larger than the critical angle of the first interface between high–low RI media. Previous studies suggested the ROTE for potential application in high-performance devices such as optical switches [15,16] and RI sensors [19,20].

In a broad category, research on the ROTE is part of the continuous efforts to investigate the analogies between wave optics and quantum mechanics, which have provided great opportunities for transferring new ideas, concepts, and methods among apparently different physical fields [21]. Such analogies benefit both optics and quantum mechanics in many aspects. For example, the analogy of quantum physics and optics offers a feasible approach to visualize ultrafast phenomena in the quantum field. Several basic physical properties of electron tunneling, such as tunneling time, superluminal effect and phase delay, are explored using the photon tunneling model [22–27]. In the 1990s, Chiao et al. [26] and Lee et al. [27] applied the optical barrier structure to study the fundamental properties of tunneling, such as tunneling time, phase time and post-tunneling positions. In 2013, George M. Gehring et al. measured single-photon time delay in a double-prism frustrated total internal reflection structure [17]. And Yin-Jung Chang investigated lasing-like transmission in TE resonant optical tunneling through an asymmetric, single-barrier potential system in 2014 [13].

Meanwhile, the quantum analogy of optics provides a refreshed view to analyze complex optical systems with unprecedented functions. The photonic crystal borrows the idea of electronic bandgap when electrons move in the crystal lattice, and thus generates the optical bandgap for photons [28]. Regarded as a classical theory, this concept vividly and precisely describes the features of light propagation in periodic dielectric structures and leads to a flourishing research area

* Corresponding author at: MicroNano System Research Center, Taiyuan University of Technology, Taiyuan 03002, China .
** Corresponding author.
E-mail addresses: sunboa-sang@tyut.edu.cn (S. Sang), xuming.zhang@polyu.edu.hk (X. Zhang).

https://doi.org/10.1016/j.optcom.2018.07.047
Received 21 April 2018; Received in revised form 11 June 2018; Accepted 14 July 2018
Available online 17 July 2018
0030-4018/

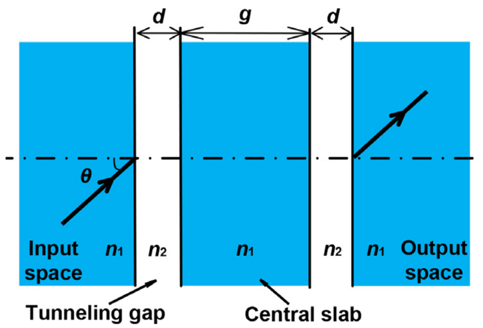

Fig. 1. Schematic diagram of the ROTE structure.

of fundamental and practical interest (e.g., photonic bandgap crystals). Furthermore, like the scanning tunneling microscopy, the photon tunneling microscopy with ultrahigh spatial resolution has been developed to use an optical tip to tunnel photons for 3-D topographic imaging [29–31].

On the basis of the analogy, the quantum interpretation of ROTE was briefly mentioned in the authors' previous review article [7]. However, the analysis equations of the ROTE remain untouched. In this work, the physical mechanism of ROTE can be examined from two origins: the optical interpretation and the quantum interpretation. The former originates from the wave nature of light and regards the ROTE as the propagation of lightwave through a multilayered film. The latter is derived based on the particle nature of light and treats the ROTE as the photons going through a quantum well, like the electrons in resonant tunneling diodes. Fundamentally, the optical interpretation is based on the Maxwell's equations, whereas the quantum interpretation is based on the time-independent Schrödinger equation. Previous studies mostly analyzed the ROTE using the transfer matrix method (TMM) [7,19], here we will go further to conduct the optical simulation using the finite-difference time-domain (FDTD) method and will present the optical analysis using the plane wave expansion (PWE) with the aim to show more details such as electric field distribution and band structure of ROTE. These results also act as the reference to verify the quantum model. Besides, this paper will describe the detailed derivation of the quantum model and finally give the important expressions of the transmission spectrum and the peak position. This is the first time that the corresponding analogy contributes to the design/characterization of applied photonic devices.

2. Optical interpretation

In this section, the ROTE is regarded as a multilayer system and analyzed based on the Maxwell's equations. Compared with the quantum interpretation, the optical interpretation analyzes ROTE from a classical perspective. The physical mechanism of ROTE is presented in detail by using various simulation methods. The distinct characteristics of ROTE can also be revealed by comparing the ROTE with other similar optical models, such as the photonic crystals and Fabry–Pérot etalons. In the classical interpretation, the electromagnetic field distribution of the ROTE structure can be presented using the FDTD simulation. The existence of the ROTE mode is verified in accordance with the results PWE.

2.1. FDTD simulation of electric field distribution

The simulation model of the ROTE structure is shown in Fig. 2 (Lumerical FDTD). In the ROTE structure, the medium of the tunneling gap (i.e., the low RI layers) is set as air, whereas that of others (i.e., high RI layers) is chosen to be silicon. Thus, the materials from the input to the output space are made of silicon–air–silicon–air–silicon. The

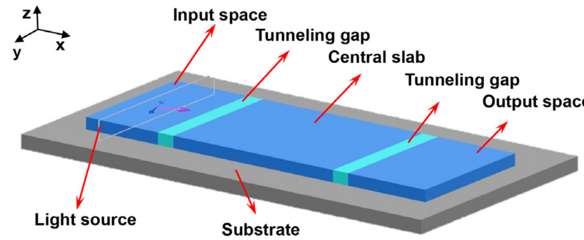

Fig. 2. Optical structures of the ROTE in the FDTD simulation.

Table 1
Parameters of the rote structure.

Parameter	Symbol	Value	
		S-pol.	P-pol.
Incident angle	θ	18.0016°	18.0016°
Width of central slab	g	15.5 μm	15.5 μm
RI of input and output space	n_1	3.420	3.420
RI of central slab	n_1	3.420	3.420
RI of tunneling gap	n_2	1.000	1.000
Width of tunneling gap	d	0.5 μm	1 μm

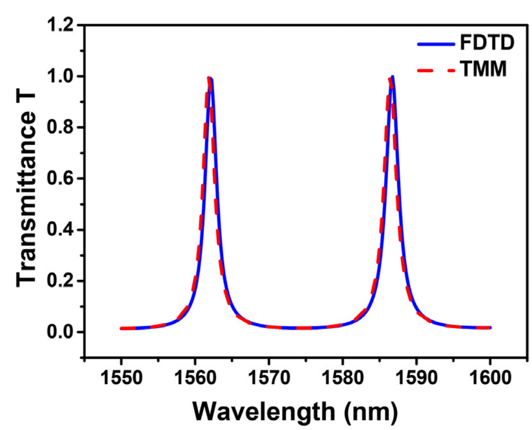

Fig. 3. Transmission spectra of ROTE obtained by the TMM and the FDTD when the light is in P-polarization.

structural parameters of the model are listed in Table 1. To form the total reflection, the angle θ of the incident light is set to be 18.0016°, larger than the critical angle (17.0016°) by 1°. When a linearly-polarized light passes through the integrated ROTE structure, the power monitor collects the transmission power in the output space. Since the absorption of silicon is extremely low in the near-infrared band, the material absorption is neglected.

For the above ROTE structure, Fig. 3 shows the transmission spectra for P-polarization as obtained by the FDTD simulation and the TMM calculation. The TMM has been widely applied to multilayer optical structure, and the TMM model of ROTE can be found in authors' previous work [19]. In Fig. 3, the curves given by the two methods almost overlap, verifying the correctness of the FDTD simulation. Sharp transmission peaks are obtained at the wavelengths of 1562.05 and 1586.75 nm, the transmittance (defined as the ratio of transmitted optical power to the incident power) reaches 1.0 (i.e., 100%). This finding indicates that the incident light can completely pass through even though the incident angle is beyond the total internal reflection (TIR) critical angle at the first high-low interface. This is one of the distinctive features of ROTE as compared to the other effects using the evanescent waves (e.g., frustrated total internal reflection), of which transmittance is < 100%.

To further analyze the distribution of electric field propagation, incident wavelengths with different transmittances T = 1, 0.52 and