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# Coherent electron transparent tunneling through a single barrier within a Fabry-Perot cavity

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ABSTRACT

Electromagnetic wave and quantum DeBroglie wave have many parallels between each other. We investigate the quantum mechanical counterpart of electromagnetic resonant tunneling through a non-absorbing metal layer. It is confirmed that an electron also has transparent transmission through a single barrier within a Fabry-Perot like cavity. This tunneling structure is actually a distortion of the Fabry-Perot echelon. We find that for a specific resonant electron energy, the cavity length is related to the electron's DeBroglie wavelength; and the single barrier can be located at a series positions with an interval equal to a half of the DeBroglie wavelength, not just at the center of the cavity. This tunneling phenomenon will have novel applications in quantum devices such as the resonant tunneling diode and scanning tunneling microscope. The results of this paper should also have impact on related electromagnetic research and application.

## 1. Introduction

Tunneling effect is an important quantum or electromagnetic wave penetration phenomenon. In quantum mechanics, an electron can leak out of a classically forbidden wall; and in an optical waveguide, the electromagnetic fields are not just confined in the guided core, but also appear in the cladding layers. Some modern nano-scale detection devices, such as the scanning tunneling microscope (STM), are based on quantum tunneling effects [1]. In the resonance tunneling case, with the classically forbidden potential barriers, the transmission of electrons can even reach unity to achieve complete transparency without reflection. The well-known application in this category is the double-barrier semiconductor structure that has been widely used in resonant tunneling diode (RTD) or Esaki diode fabrication [2–4]. Recently, it is reported that electromagnetic waves can transparently tunnel through a non-absorbing metal barrier with the symmetric phase matching layers on both sides [5]. This new electromagnetic tunneling phenomenon has been examined to obtain transparent metals for broadband electromagnetic waves, light trapping enhancement structure for solar cells, and thermal-optic switching [6–8]. Behaving as waves, quantum particles and electromagnetic fields share many common features [8,9]. For example, the optical waveguide cross-sectional mode equation is similar to the quantum well eigen-equation; and multi-mode interference in electromagnetic wave is similar to quantum wave-function fractional revival [10,11]. In this paper, we will systematically investigate the quantum correspondence of electromagnetic transparent transmission through a non-absorbing metal barrier reported in Ref. [5]. The discoveries in this research, such as the relation between the barrier location/cavity length and the resonant

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DeBroglie wavelength, will not only enhance the physics understanding of electron tunneling phenomena, but also benefit related electromagnetic research and application.

In this paper, we briefly introduce the theory in section 2 and try to link the quantum terminologies with their electromagnetic correspondences so that one can easily understand the similarity between these two different areas. We present the single barrier quantum transparent tunneling results and discoveries in section 3. This section also includes a concept study of potential RTD realization relied on the new tunneling phenomenon. Finally, we give the conclusions in Section 4.

## 2. Theory and model

As pointed out in Refs. [5], transparent tunneling through a meta-material barrier observed in electromagnetic waves corresponds to a quantum mechanics potential structure shown in Fig. 1. $V_i$ and $m_i$, where i denotes the layer index, are the potential energy and effective mass of each layer, respectively. Using the transfer matrix approach [12], in each layer, we write the static Schrödinger wave-function as

$$\begin{aligned} \psi_i(z) &= A_i e^{jk_ix} + B_i e^{jk_ix} \quad (x_i \le x \le x_{i+1}) \\ k_i &= \frac{\sqrt{2m_i(E-V_i)}}{\hbar} \end{aligned} \tag{1}$$

In Eqn. (1), E is the incident electron energy from the left side as shown in Fig. 1. Since we are interested in the tunneling effect, E is always higher than $V_1$. With consideration of the boundary conditions, the following transfer matrices relate the solutions between two adjacent hetero-junctions.

$$\begin{aligned} &\begin{pmatrix} A_i \\ B_i \end{pmatrix} = \widehat{M}_i \begin{pmatrix} A_{i+1} \\ B_{i+1} \end{pmatrix} \\ &\widehat{M}_i(1,1) = \left(\frac{1}{2} + \frac{k_{i+1}m_i}{2k_im_{i+1}}\right)\exp[j(k_{i+1}-k_i)x_{i+1}] \\ &\widehat{M}_i(1,2) = \left(\frac{1}{2} - \frac{k_{i+1}m_i}{2k_im_{i+1}}\right)\exp[-j(k_{i+1}+k_i)x_{i+1}] \\ &\widehat{M}_i(2,1) = \left(\frac{1}{2} - \frac{k_{i+1}m_i}{2k_im_{i+1}}\right)\exp[j(k_{i+1}+k_i)x_{i+1}] \\ &\widehat{M}_i(2,2) = \left(\frac{1}{2} + \frac{k_{i+1}m_i}{2k_im_{i+1}}\right)\exp[-\ j(k_{i+1}-k_i)x_{i+1}] \end{aligned} \tag{2}$$

The reflectivity coefficient R and transmission coefficient T are obtained from the total transfer matrix as follows

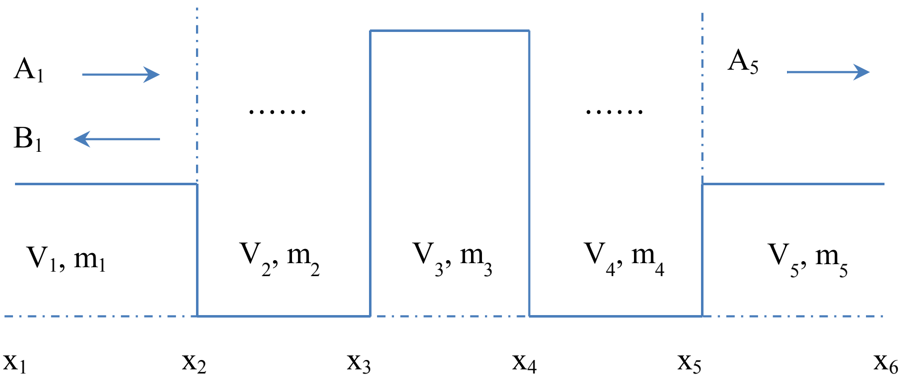

**Fig. 1.** Potential profile and related material parameters.