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Switching of transmission resonances in a two-channels coupler: A Boundary Wall Method scattering study

A. Nunes [a], F.M. Zanetti [b], M.L. Lyra [a,*]

[a] *Instituto de Física, Universidade Federal de Alagoas, 57072-970, Maceió-AL, Brazil*

[b] *Departamento de Física, Universidade Federal do Paraná, 81531-990, Curitiba-PR, Brazil*

HIGHLIGHTS

- The switching performance of a coupled waveguide device is studied via the boundary wall method.
- The method efficiently identifies all resonant transmission modes.
- Energy switching is controlled and optimized as a function of the device geometry.

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ABSTRACT

In this work, we study the transmission characteristics of a two-channels coupler model system using the Boundary Wall Method (BWM) to determine the solution of the corresponding scattering problem of an incident plane wave. We show that the BWM provides detailed information regarding the transmission resonances. In particular, we focus on the case of single channel input aiming to explore the energy switching performance of the coupler. We show that the coupler geometry can be tailored to allow for the first transmission resonances to be predominantly transmitted on specific output channels, an important characteristic for the realization of logical operations.

1. Introduction

In the last decades, the development of high-technological processes has reached the regime of quantum engineering and boosted the design, tailoring and optimization of new nano and mesoscopic devices that can perform pre-assigned tasks. Several advances have been put forward in

* Corresponding author. Fax: +55 82 3214 1645.
E-mail address: marcelo@fis.ufal.br (M.L. Lyra).

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the manufacturing of new electronic devices for which the increasing demand of miniaturized systems has impelled the search for systems that can work faster, with minimal lost, while performing basic computational functions such as logical operations. There is a plethora of nano-electronic devices such as nanocircuits, quantum switches, couplers, dephasers, isolators, multiplexers, commutators, and logic gates, among others [1–5]. Among these, the couplers have attracted especial attention due to their possible application as energy switch devices [6,7]. Most of these systems have been studied within the context of boundary value problems within the scope of quantum mechanics.

Together with the technological demand, there is a growing need for the development of new theoretical techniques to solve and characterize the behavior of quantum-based devices. Among several distinct approaches to address boundary value problems, methods based in quantum wave scattering stand out. In scattering theory, one searches for the solution of the problem involving a quantum particle interacting with a potential satisfying pre-defined boundary conditions. There are two dynamics that are taken into account in scattering studies. The first one accounts for the free particle dynamics moving without interaction with the scattering potential. The second stands for the particle dynamics when it directly interacts with the potential at the contour barriers. In perturbation theory, the scattering process is assumed to give a small correction to the free-particle state. As such, the problem is solved using the matrix S formalism [8] which relates the incident and scattered waves and depends only on dynamical characteristics of the system. In the Boundary Integral Method (BIM), which is formulated in terms of the Helmholtz equation, the wave functions are expressed as path integrals and their normal derivative along the barrier contour, with the energy eigenvalues obtained as the roots of the associated Fredholm determinants [9,10]. The Boundary Element Method is a numerical approach to the BIM on which the Fredholm determinant is obtained after a discretization of the associated integral equation [11]. Further, there are also Plane Wave Decomposition methods that are commonly used to solve Helmholtz-like equations [12].

A new scattering method has been put forward in the last two decades which can be implemented numerically using a simple algorithm to probe the solutions of boundary problems such as quantum billiards and waveguides [13,14]. This technique, named the Boundary Wall method (BWM) was conceived to reach the solution of scattering problems on which the barriers can be either open or closed, connected or disconnected, and with quite general boundary conditions. An important feature of the BWM, which is one of its major advantages when compared with standard scattering approaches, is that it produces simultaneously the correct solutions for both internal and external regions, besides its easy numerical implementation. The main mathematical object within the BWM is the so-called T matrix whose most important characteristics are the fact that it brings full information regarding the energy and geometry of the problem, thus producing direct access to the energy spectrum and transmission as a function of the scattering barrier geometry. Within such approach, the influence of the system's geometry on the transmission characteristics of coupled cavities has been recently analyzed [15]. The BWM appears as a potential tool to investigate the transmission of electronic waves through structured devices that can have their geometry systematically explored to optimize specific functions.

In the present work, we will demonstrate the versatility of the BWM to study the transmission properties of model devices. We will consider a directional coupler consisting of two input channels, an interaction region, and two output channels. This structure has the basic elements of several practical devices such as switches and logical gates (see Fig. 1). Here we will be particularly interested in the possible performance of energy switch and its dependence on geometrical aspects of the structure. We will show that the elements of the T matrix capture the main characteristics of the transmission spectrum. Further, we will unveil that the distinct resonant transmission modes are affected differently by the system geometry. By exploring the switching performance as a function of two of the device's geometric parameters, we will show that the transmission resonant modes can be driven towards distinct output channels.

The work is organized as follows: in Section 2 we will provide a detailed description of the BWM. In Section 3, we will describe the directional coupler model system we are going to study and show the main results obtained by the BWM concerning the transmission spectrum and switch performance of the proposed device. In Section 4 we summarize our work, draw our main conclusions and discuss on future perspectives of the BMW in the study of structured quantum devices.