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Transmission through Surface Disordered Waveguides and Nanowire as Drastic Influence on Coherent Scattering

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ABSTRACT We have studied transmission through surface disordered waveguides in general and a solid basis. Our results showed that desired transmission properties on a waveguide through the roughness of its boundaries can be obtained. This surface scattering approach predicted that how mode specific scattering lengths in waveguides depend on the details of system's surface roughness. It was shown that previously neglected square-gradient scattering mechanism and predicted that this new scattering mechanism has to be considered together with the conventional amplitude scattering mechanism. Square gradient scattering is related to higher order terms in the disorder strength it can be the major scattering mechanism in system with modest disorder. Surface scattering theory is for long range correlations, which seems to restrict its applicability to very long waveguides. We have extended this surface scattering theory to short, individual waveguides. We found that an observed shift of the amplitude scattering gap could be attributed to the nonvanishing disorder strength. We also found that short wave lengths can exhibit effects predicted for systems with long range correlations leading to drastic changes in their transmission properties. The obtained results were compared with previously obtained results of theoretical and experimental works and were found in good agreement.

KEYWORDS surface disordered, waveguides, roughness, boundary-scattering.

INTRODUCTION

Khurgin et al. [1] showed that some devices like quantum cascade laser and gated graphene nanoribbon by Hau et al. [2] and Evaldsson et al. [3] the scattering at rough boundaries was identified as one of the dominant factors that limited the device performance. Surface roughness effects might hold the key for the explanation of anomalously large persistent currents in met al.lic rings and are actively used to control gravitationally bounded quantum states of neutrons studied by Jenke et al. [4] as well as enhanced the thermoelectric performance of nanowires as indicated by Hoch Baum et al. [5]. Frisk [6] studied the effects induced by surface scattering often are the key for the understanding both of natural phenomena like the scattering of underwater waves at a rough ocean seabed as well as of manmade devices like optical fibers and waveguides presented by Chaikina et al. [7] and Maker et al. [8]. The study of photonic crystal devices by Gam et al. [9] metamaterials by Mardudin [10], thin met al.lic films layered structure, nanowires optical diffraction tomographs by Maire et al. [11] and confined quantum systems in general was made. Our analysis was set to show that conventional surface scattering theories for the coherent transmission through wave-guided lack significant ingredients. Our aim was to determine the transmission properties of system from a given rough boundary profile, numerical calculations can sometimes help to overcome these deficiencies of existing analytical methods given by Zhao et al. [12]. We designed a boundary such as to obtain desired transmission properties; improved analytical models are indispensable which provided the functional dependence of the transmission properties on the boundary profile.

METHOD

We performed a experiment using the microwave setup. The studied scattering system consists of a planar waveguide with met al.lic walls with a rough central part of length L = 80 cm which features two undulating, symmetric boundaries, $z = \pm\left[d/2 + \sigma\xi(x)\right]$. The average width of the scattering part was d=10cm and the roughness variance was σ^2. We have chosen a modest disorder of $\frac{\sigma}{d} \approx 9\%$, $\sigma \approx 8.7nm$. The boundary profile function $\xi(x)$ has zero mean, $\xi(x) = 0$, unit variance, $\xi^2(x) >= 1$, and features a binary correlator by

$$\langle \xi(x)\xi(x')\rangle = W(x - x').$$

In the convention of the Surface scattering theory the angular brackets stand for an ensemble average over different realizations of $\xi(x)$. By assuming the ergodicity of $\xi(x)$, the average can be performed along a single surface profile. The quantity $W(x)$ can also be treated as the autocorrelation function of the boundary profile used. For vanishing disorder the wave vector is quantized along the transverse direction (z), yielding n propagation modes whose wave numbers in guiding direction (x) at frequency v are given by

$$k_n = \sqrt{\left(\frac{2\pi v}{c}\right)^2 - \left(\frac{\pi n}{d}\right)^2}$$

The chosen up-down symmetry of the disorder profile prevents mixing of odd and even modes during the scattering process. We have used a single finite boundary realization. The partial transmittances T_n correspond to the average over the most probable realizations of the surface disorder.

$$\langle Tn\rangle = \exp\left(\frac{-2L}{L_n^{(loc)}}\right)$$

For isolated modes the localization length $L_n^{(loc)}$ of the nth propagating mode n=1,2, is twice the corresponding back scattering length $L_n^{(loc)} = 2L_n^{(b)}$, a quantity which has been calculated with surface scattering theory

$$\frac{1}{L_n^{(b)}} = \frac{1}{L_n^{(b).(AS)}} + \frac{1}{L_n^{(b).(SGS)}}$$

Where AS = amplitude scattering and SGS are the square gradient scattering mechanisms.

$$\frac{1}{L_n^{(b).(AS)}} = \frac{\sigma^2}{d^6}\frac{4\pi^4 n^4}{k_n^2}W\left(2k_n\right)$$

$$\frac{1}{L_n^{(b).(SGS)}} = \frac{\sigma^4}{d^4}\frac{\left(3+\pi^2 n^2\right)^2}{18k_n^2}S\left(2k_n\right)$$

Correspondingly these transmission characteristics are specified by two different roughness power spectra.

$$W\left(k_x\right) = \int_{-\infty}^{\infty} W\left(x\right)\exp\left(-ik_x x\right)dx.$$

$$S\left(k_x\right) = \int_{-\infty}^{\infty} W^{"2}\left(x\right)\exp\left(-ik_x x\right)dx.$$

Where $W\left(k_x\right)$ the Fourier is transform of the roughness height correlator and is called roughness height power spectrum. $S\left(k_x\right)$ is roughness square gradient power spectrum. Since for Gaussian random process it is the Fourier transform of the roughness square gradient correlator $\left\langle \xi'^2\left(x\right)\xi'^2\left(x'\right)\right\rangle - \left\langle \xi'^2\left(x\right)\right\rangle^2 = 2W^{"2}\left(x-x'\right)$.

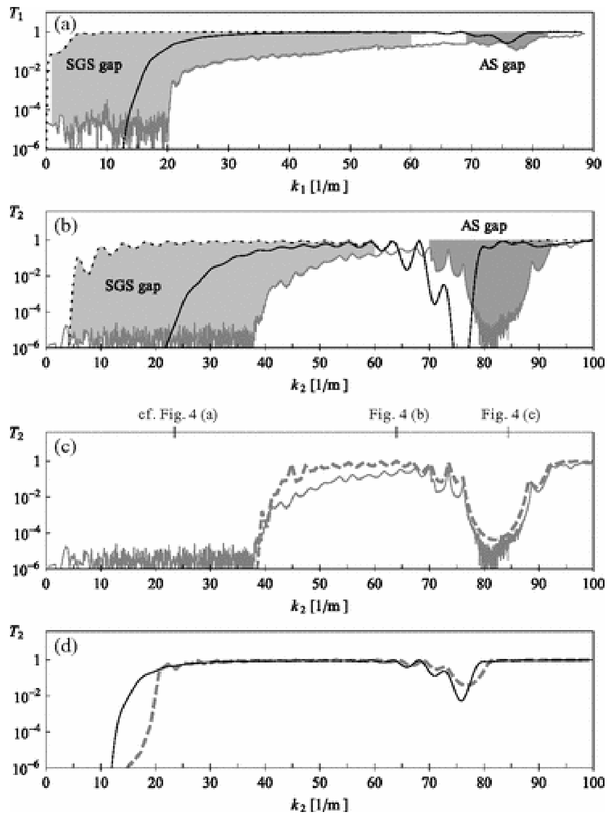
In order to observe the two scattering mechanism separately we have generated a rough boundary profile $\xi\left(x\right)$ with a power spectrum $W\left(2k_n\right)$ being non zero only within a small k_n range. The localization length and potential transmission gaps outside this range is determined by $S\left(2k_n\right)$. For this we have chosen the roughness height power spectrum in rectangular form

$$W\left(k_x\right) = \begin{cases} \dfrac{\pi}{2\left(k_+ - k_-\right)} & \text{for} 2k_- - < \left|k_x\right| < 2k_+ \\ 0 & \end{cases}$$

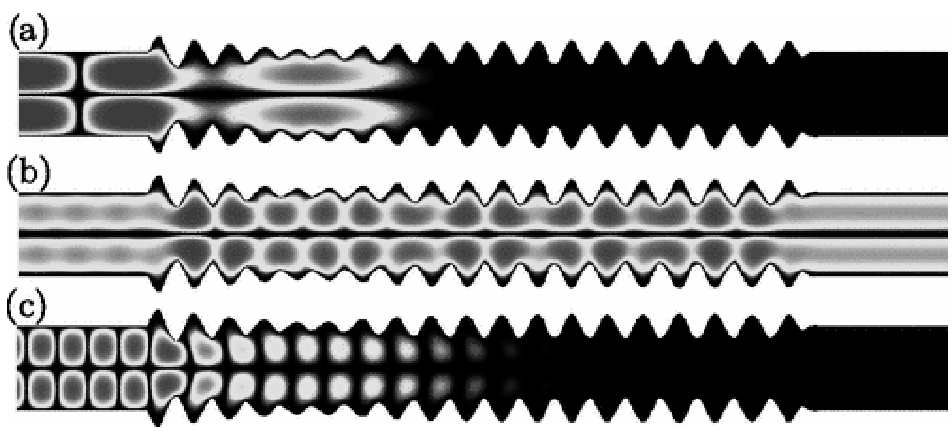
Respecting the normalization $W\left(0\right)=1$.

RESULTS AND DISCUSSION

Graph (1) shows the resulting transmission curve for the first and second mode feature two transmission gaps curves in graph (1) (a) and (1)(b). Surface scattering theory is shown in the graph. The first transmission gap is located near the opening of the modes and the second gap appears around $k_n = 80\,\mathrm{m}^{-1}$. This corresponds between the experiment and theory allows us to associate the observed gaps with the square gradient scattering and amplitude scattering mechanism. We have calculated theoretical curves where the square gradient scattering term is explicitly neglected as shown in graph (1)(a) and (1)(b). These curves only contain the amplitude terms and do not display the previously indentified square gradient scattering gaps. We have observed at the central message transmission through surface disordered waveguides manifests clear signatures of the amplitude and the square gradient scattering mechanism. The square gradient scattering contribution to transmission even dominated the conventional amplitude scattering contribution and both mechanisms extended bands gaps in the transmission. We have calculated all scattering matrix elements and the corresponding scattering wave functions as shown in graph (2) in the waveguide with an extended version of the modular Green's function method which is based on a finite difference approximation of the two dimensional scattering geometry. Both the amplitude scattering gap and the square gradient scattering gap for the numerical transmittance T_2 match the experimental values.



Graph 1: Measured transmittance T_n for (a) the first $(n=1)$ and (b) the second mode $(n=2)$. The corresponding theoretical prediction is shown as solid black curve.



Graph 2: Numerically calculated wave functions for transmission in the second mode. The corresponding k_2 values of (a) 23.46m^{-1}, (b) 64.02 m^{-1} and (c) 84.39m^{-1}

CONCLUSION

We have studied the transmission through surface disordered waveguides and effect of nanowire on coherent scattering. We found that the observed shifts and broadenings of the gaps are not experimental artifacts but details of omitted by surface scattering theory. The latter was derived for perturbatively small disorder amplitude. A theoretical study of antenna coupling predicts that coefficients depend only weakly on frequency such that we can regard them as fitting constants. Due to imperfect coupling to the antennas and losses at open ends, the maximal measurable transmission is of the order of 10-3 as reflected. We have obtained much better agreement between theory and numerical values. The amplitude scattering gap is now both less broad and shifted to the predicted interval and the square gradient scattering gap is suppressed as its dependence $\sim \sigma^4$. Our result allows us to visualize the scattering wave functions at characteristic frequency values. The obtained results are in good agreement of previously obtained results.

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