Is ball lightning "Anderson Localization"?: Localized and enhanced fields in a corridor with irregular-shaped metal walls

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We propose that "Anderson Localization" is a possible explanation for ball lightning on the basis of computer simulation of electromagnetic wave propagation in a corridor with irregular-shaped metal walls. It was found that the electromagnetic wave could be strongly localized and its strength could be strongly enhanced in small regions in the corridor under specific conditions. Similar effects may create electric fields strong enough to cause electrical breakdown conditions in the open atmosphere, and this phenomenon may be observed as ball lightning. © *1997 American Institute of Physics.* [S0003-6951(97)02352-8]

Ball lightning is considered a real phenomenon which occurs in the natural atmosphere. Although a number of theoretical works concerning ball lightning have been published, a number of mysteries still remain. One interesting theory for ball lightning, proposed first by Kapitsa,[1] is that ball lightning is a fireball resulting from electric discharges created by the interference of strong electromagnetic waves from thunder clouds. Kapitsa's theory states that the energy of ball lightning is supplied by electromagnetic waves, and this proposal has been developed both theoretically[2–6] and experimentally.[7,8] Ohtsuki and Ofuruton,[7] in one of their experiments with microwaves, produced a plasma fireball in a metal cavity. They showed that this plasma fireball could travel through the dielectric slab without destruction and could move against the wind, which are just the mysterious characteristics of ball lightning that have been reported by eyewitnesses. In this electromagnetic-interference hypothesis, it is necessary to employ some kind of focusing or localization of the electromagnetic waves in order to make the electric field strong enough to establish the breakdown condition in a localized region of the open atmosphere.

Anderson indicated that waves may be localized into a finite spatial region in disordered or random media because of constructive interference occurring within the randomly scattered waves, and this effect is often called "Anderson Localization".[9] The localization of electromagnetic waves in random media has been extensively investigated.[10–14] Frich *et al.* analyzed the reflection of electromagnetic waves by one-dimensional random media.[15] They showed theoretically that the wave can be localized and its amplitude can be strongly enhanced due to "stochastic resonance" in random media. Since there are many scattering objects located at random positions in the complicated topography, the natural environment can be regarded as a disordered or random media for electromagnetic waves. This disordered condition is necessary for localization and enhancing the waves.

In this letter, we propose that Anderson Localization of electromagnetic waves in natural environments may be a cause of ball lightning. It is possible to consider the random fluctuations of the index of refraction in the air as a random media for electromagnetic waves. However, it was found that the normal fluctuation of the index of refraction in the air due to changes in temperature, atmospheric pressure, and humidity are too small to cause significant localization or enhancement of electromagnetic waves.

In order to investigate this hypothesis concerning the cause of ball lightning, we considered the propagation of electromagnetic waves in a corridor which has irregular-shaped metal walls. Simulation results showed that the electric field inside the corridor with the irregular walls could become far stronger than that of the incident electromagnetic waves in localized regions. This effect can produce electric discharges in small spatial regions, i.e., ball lightning.

The geometry of the problem considered in this letter is shown in Fig. 1. Two-dimensional straight waveguides, whose widths are given by k_0a, were aligned to a corridor with irregular-shaped metal walls whose length is given by k_0b as shown in Fig. 1, where k_0 is a wave number resulting from 2π/wavelength. It was assumed that both straight waveguides satisfied the single-mode condition. The space in the waveguides and the corridor were filled with air. A TE dominant guided mode, which has only the z component of the electric field $E(x,y)$, was assumed to be incident from the left straight waveguide. It was possible to solve the problem of reflection and transmission of the guided mode by a corridor numerically, as shown in Fig. 1, with high accuracy by use of the boundary-element method based on guided-mode extracted integral equations (GMEIEs).[16] It was con-

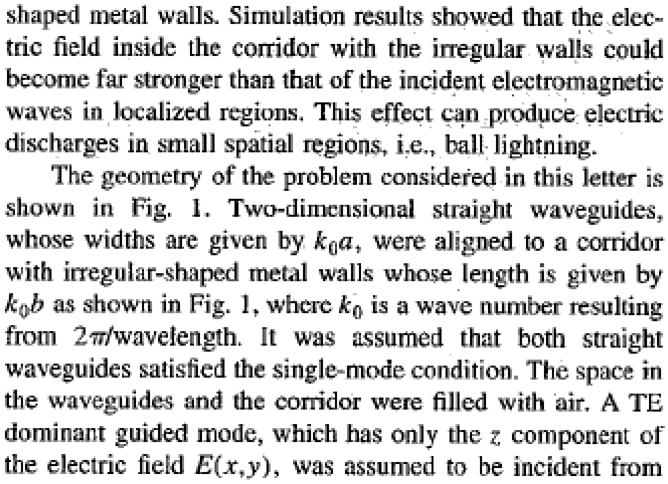

FIG. 1. Geometry of the problem.

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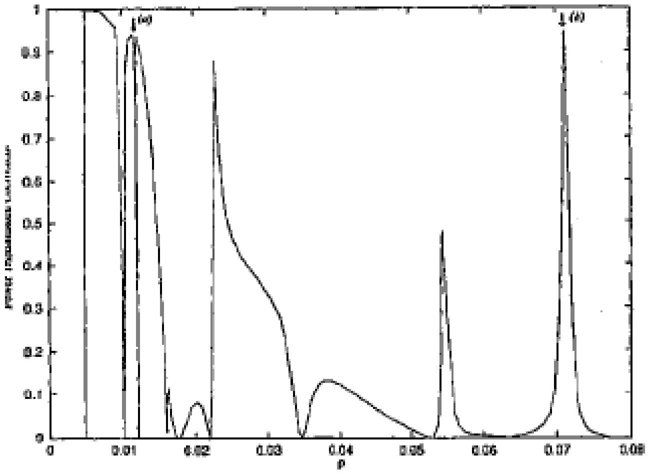

FIG. 2. Transmission characteristics of the corridor as shown in Fig. 1.

firmed that all the numerical results in this letter satisfy the energy conservation law within an accuracy of 1%.

The shapes of the irregular walls in the corridor were determined by the summation of Gaussian shot pulses that obey a stochastic Poisson process.[17] The irregular-shaped walls were placed such that their average wall positions coincided with the position of the straight waveguides as shown in Fig. 1. The average values of the upper and lower wall position of this corridor are zero measuring each wall position from each straight waveguide. The auto-correlation function of the wall positions can be written, using Campbell's theory,[17] as

$$\phi(k_0\tau)=\sigma^2\cdot\exp[-(k_0\tau)^2/(k_0l)^2], \tag{1}$$

where $\sigma^2=\phi(0)$ is a variance of the wall position and k_0l is the transverse correlation length. It should be noted that all lengths in this letter were normalized by the wave number k_0. Parameters used in the numerical calculations are given by $k_0a=1.99\pi$ (0.995×wavelength), $k_0b=230$ (36.31×wavelength), $k_0l=4$ (0.64×wavelength).

Given the condition that the construction of the irregular-shaped walls was fixed to a given sample stochastic Poisson process, the transmission characteristics were calculated. The dependence of the power transmission coefficient on the normalized standard deviation of the wall position defined by $\rho=\sigma/(k_0a)$ is shown in Fig. 2. It was found that, when values of ρ were small (i.e., $\rho<0.015$), the electromagnetic waves could easily transmit through the corridor. When values of ρ were large (i.e., $\rho>0.05$), the electromagnetic waves could not easily transmit through the corridor due to interference by the waves scattered from the irregular walls. These results are reasonable from a physical viewpoint. It was also found that there are several resonance points as shown in Fig. 2, which give small or large transmissions.

The distributions of the electric fields in the corridor were also calculated. The distributions of the electric fields inside the corridor are shown in Figs. 3 and 4 for the resonant points (a) and (b) marked by arrows in Fig. 2. The z axis in Figs. 3 and 4 represents the absolute value of the electric field normalized by the amplitude of the incident TE mode. The practical shape of the corridor for each numerical example is also shown in the upper inset of Figs. 3 and 4.

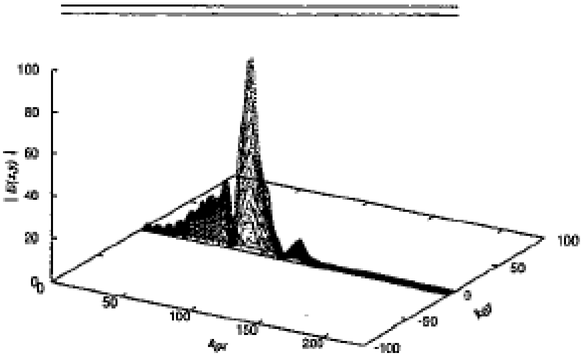

FIG. 3. Absolute value of field distribution $|E(x,y)|$ in the corridor at point (a) in Fig. 2 ($\rho=0.0119$).

It was found that the electromagnetic wave was localized and its field was enhanced in small regions in the corridor at each resonance point, as shown in Fig. 3 for $\rho=0.0119$, and in Fig. 4 for $\rho=0.0712$. The electric field for $\rho=0.0119$ [point (a) in Fig. 2] was up to 100 times larger than that of the incident wave as shown in Fig. 3. The electric field for $\rho=0.0712$ [point (b) in Fig. 2] was up to 30 times larger, as shown in Fig. 4. (Note that the z-axis units in Fig. 3 are different from those in Fig. 4.) The phenomenon at point (a) in Fig. 2 resembles the stochastic resonance in one-dimensional random media proposed by Frich *et al.* because the incident wave is almost totally reflected.[5] It is possible that an electric discharge will occur in a region where the enhanced electric field satisfies the breakdown condition, and it is possible that this discharge will be observed as ball lightning. It should be noted that the cross-section size of the discharge region, where the enhanced field strength exceeds a given value, can become smaller than that of the wavelength of electromagnetic waves, as shown in Figs. 3 and 4. (Note that the width of the straight waveguide was about one wavelength.)

The derivatives of the electric field normal to the boundary on the walls ($\partial E(x,y)/\partial n$) are proportional to the current distributions on the walls, and their absolute values ($|\partial E(x,y)/\partial n|$) on the upper wall are shown for $\rho=0.0015$, $\rho=0.0119$, and $\rho=0.0712$ in Fig. 5. The results for $\rho=0.0015$ were almost the same as those of $\rho=0$, i.e., a straight waveguide. It was found that large current distributions existed on the wall in the vicinity of the localized and

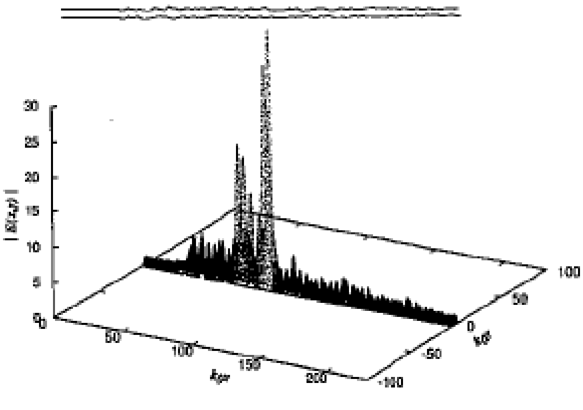

FIG. 4. Absolute value of field distribution $|E(x,y)|$ in the corridor at point (b) in Fig. 2 ($\rho=0.0712$).

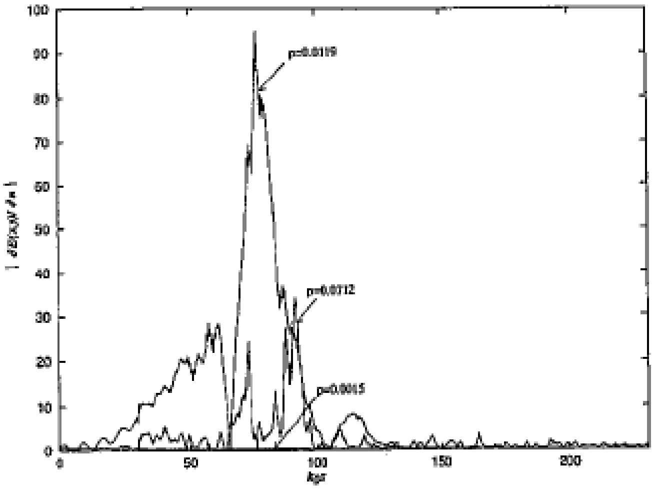

FIG. 5. Absolute value of normal derivative of the electric field $|\partial E(x,y)/\partial n|$ on the upper wall ($\rho=0.0015$, $\rho=0.0119$, and $\rho=0.0712$).

enhanced fields of Figs. 3 and 4. If this theory is valid as an explanation of ball lightning, it would mean that large currents exist on metal conducting objects in the vicinity of the ball lightning. These large currents would influence conducting objects in the vicinity of the ball lightning, and such phenomena have been reported by eyewitnesses.[18] The environmental situation considered in this letter is similar to that in a valley, in a street, in a submarine, or in the fuselage of an airplane.

To summarize, we have proposed Anderson Localization as a possible explanation for ball lightning on the basis of computer simulation of electromagnetic wave propagation in a corridor with irregular-shaped metal walls.[19] It was found that the electromagnetic waves could be strongly localized and their strength could be strongly enhanced in small regions of the corridor under specific conditions. These effects could create electric fields strong enough to cause electrical breakdown conditions in the open atmosphere, i.e., ball lightning. In this letter, only the simplest problem was considered due to the limited ability of the computer systems. However, the results presented here can be used as a starting point for further investigations toward more accurate theory of ball lightning.

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