Experimental Demonstration of Epsilon-Near-Zero Behavior of a Waveguide at Cutoff and Its Tunneling and Energy Squeezing Properties

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Metamaterials with near-zero permittivity and near-zero index of refraction possess interesting electromagnetic properties [see, e.g., M. Silveirinha and N. Engheta, "Tunneling of electromagnetic energy through subwavelength channels and bends using epsilon-near-zero materials", Physical Review Letters, Vol. 97, 157403 (2006); A. Alù, M. Silveirinha, A. Salandrino, and N. Engheta, "Epsilon-near-zero metamaterials and electromagnetic sources: tailoring the radiation phase patterns", Physical Review B, Vol. 75, 155410 (2007)]. Some of these effects may be interpreted in terms of the intrinsically long wavelength supported by such a medium, which makes physically large structures appear to be electrically small and yielding surprising "static-like" behavior for time varying fields. In particular, this is the case for the anomalous resonant tunneling through narrow waveguide channels and bends when filled by ε-near-zero metamaterials.

Here, we experimentally demonstrate this phenomenon by mimicking the zero-permittivity properties with a simple waveguide geometry operating near cutoff. In fact, a rectangular metallic waveguide near the cutoff of its dominant mode effectively behaves in many ways as a material with near-zero permittivity, since the guided wavelength is very long. For a given operating frequency, we reduce the permittivity within a section of the waveguide, with respect to the surrounding parts, such that this region operates at cutoff. Upon reducing the E-plane of this waveguide section, realizing a narrow channel with cross-sectional area being less than $1/30^{th}$ of the original value, we measure near unity transmission as predicted from our theory. This opposes the intuition that a drastic E-plane discontinuity would create large reflection. Moreover, we measure near-zero phase difference between the input and output plane within this cutoff region, confirming the generation of an extremely long effective wavelength inside the thin channel. This behavior is consistent with what is expected from a channel of the same geometry filled with ENZ materials. This tunneling effect is independent of variation in waveguide height and length. As long as the channel height remains small, we can introduce any number of sharp bends with impunity, causing neither reflection nor loss. Additionally, the near-zero phase difference between input and output plane is not affected by changes in device length or the addition of bends. The combination of these properties gives the waveguide a "wire-like" character which might find applications in supercoupling, signal routing, remote sensing, and energy squeezing.