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Study of refraction of a micro plain wave by a wedge

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Abstract
Refraction of a microwave plane wave by wedge with exact characterization of g and E is evaluated by a ray approach. Snell's law is used for the lossless wedge, while exact formulations are used for the propagation constants and angle in the lossy wedge. The heavily lossy wedge produces negative refractions. Data are given on the loss factor that allows Snell's refraction to be exactly reversed by lossy refraction, and the internal angle in the lossy wedge.

Keywords: lossy, wedge, produces

Introduction
The possibility of designing microstructured materials that interact with electromagnetic waves in a controlled and desired way opens new research avenues that may enable the realization of novel compact resonator, and waveguides that may overcome diffraction limits [1, 4], which were thought insurmountable. Some interesting and promising opportunities include the realization of imaging devices with super-resolution [5, 7], or the transmission of waves through very narrow channels with great electric field enhancement [8].
The purpose of this paper is to show via microwave calculations that loss can produce negative refraction, i.e., beam reversal. The model consists of a dielectric wedge illuminated by a microwave plane wave. The latter is provided by a linear array of isotropic line sources parallel to the wedge edge, and spaced λ/4 to avoid grating lobe complications.

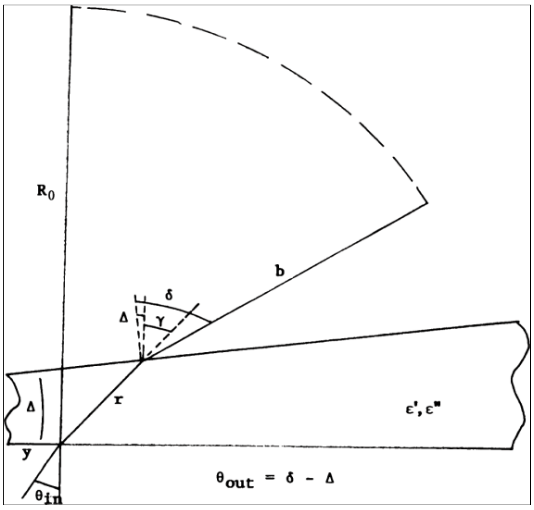

Fig 1: Wedge geometry

Dielectric wedge parameters
For a general dielectric wedge the ray angle inside the wedge is not given by Snell's law nor is the exit angle. Also the propagation constant inside the wedge is not simple $k\sqrt{\varepsilon'}$, where k=2π/λ. The field in the wedge is inhomogeneous [9] so that constant amplitude and constant phase surfaces do not coincide. The rays are normal to the constant phase surface. The real and imaginary parts of propagation constant for a general dielectric medium are [9, 10].

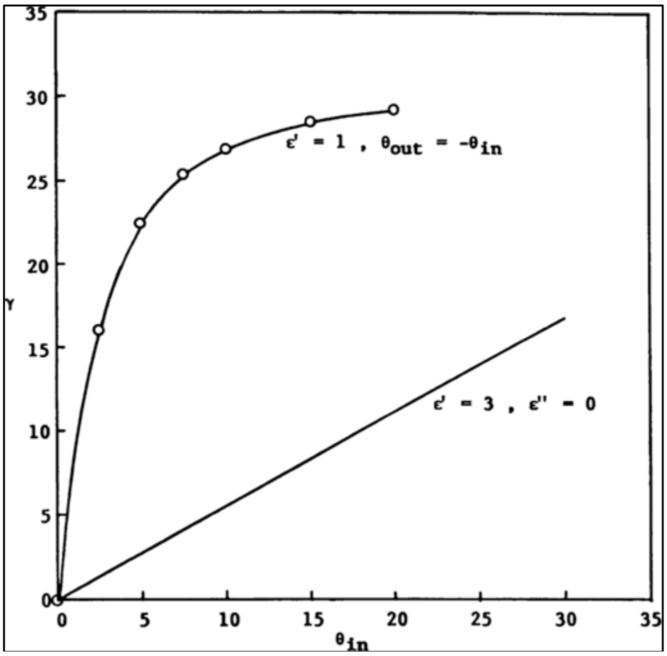

Fig 2: Angle γ in wedge

$$\frac{\beta}{k} = \sqrt{\varepsilon'}\sqrt{\frac{\sqrt{1+(\varepsilon''/\varepsilon')}+1}{2}}$$

$$\frac{\alpha}{k} = \sqrt{\varepsilon'}\sqrt{\frac{\sqrt{1+(\varepsilon''/\varepsilon')^2}-1}{2}}.$$

Loss factor tanδ = ε"+ε'; but δ is also used below for an angle. Conductivity is σ= ωε". Σ is not used as a parameter as it introduces frequency.

For a lossy medium snell's (1) is complex, and is replaced by

$$\sin\theta_{\text{in}} = \frac{jk\sin\Psi}{\alpha+j\beta}.$$

The actual refraction angle Ψ in the wedge is given by [1]

$$\Psi = \arctan\frac{k\sin\theta_{\text{in}}}{q}$$

Where

$$q = \alpha s\sin\zeta + \beta s\cos\zeta$$

With

$$s\exp(j\zeta) = \sqrt{1-\left(\frac{jk\sin\theta_{\text{in}}}{\alpha+j\beta}\right)^2}.$$

ε' and ε", and θ_{in}. the refraction angle Ψin the wedge can be calculated. For the ray exiting the wedge the same formulas and used, with appropriate interchange of symbols.

Calculated Results

Refer to Fig [1] for key distances and angles. If y is the distance along the array, the slant path r through the dielectric is

$$r = \frac{y\sin\Delta}{\cos(\gamma+\Delta)}.$$

For a given exit angle, array field is summed with the usual array phase of

$$e^{jky(\sin\theta-\sin\theta_0)}$$

And decrement of $e^{-\alpha r}$. An array length of four wavelengths (16 elements at λ/4 spacing) is used, giving a beamwidth of approximately 15 deg. The array starts 1λ from the wedge apex. A wedge of 30 deg. Included angle gives a wedge thickness normal to the input face varying roughly from .5λ to 2λ over the array length. A program check is made for ε' = 3, ε"=0. The θ_{out} values are just these perdicted by (3) and (4), and the beam pattern is as expected. For each exit angle the value of en that produce reversal of exit angle $\theta_{ex} \rightarrow -\theta_{ex}$ is calculated. Exit angles of .5,1.0,2.5,5.,7.5,10,12.5,15,17.5 and 20 deg. Are used with ε' =1. Double precision is used for all calculations due to the large exponential attenuation. Fig.3 show ε" versus θ_{out}. The reversed beams show the expected beams show expected beam pattern, with appropriate beamwidths, for each exit angle.

The lossy 30 deg. Wedge has a 5 deg. Beam angle reversal, for ε"=535, and with α/k=16.240. Exp (-αr)=4.705 E-16. Note that for ε">> ε', the attention constant is independent of ε', and is ε/k=ε.

These results are specific for a 30 deg. Wedge, and for the wedge thickness over the array length. In general, smaller wedge angles Or a thinner wedge along the array length require larger ε" (more loss) for beam reversal. The purpose here is not to provide design trade data, but only to show that loss alone in a wedge can reverse a microwave beam.

Beam reversal can be caused by material (dielectric) loss, or by a wedge transmission coefficient that is small. This relates to the NIM structures consisting of layers, with each layer including closely spaced long wires (in wavelengths) with interspersed half-loops, etc. from Marcuvitz [11] the reactance of single grid of parallel wires of radius a and spacing d is

$$\frac{x}{z_o} \cong \frac{d\cos\theta}{\lambda}\ln\csc\frac{\pi a}{2d}.$$

For example, wires of d/a =20 and d/λ = .01 give x/z_0 = .02545. A single layer gives a transmission (power) coefficient of .0968 or -10dB. Multiple layers will reduce the transmission significantly. However, the wave in the NIM material may be evanescent, and much more lossy [12].

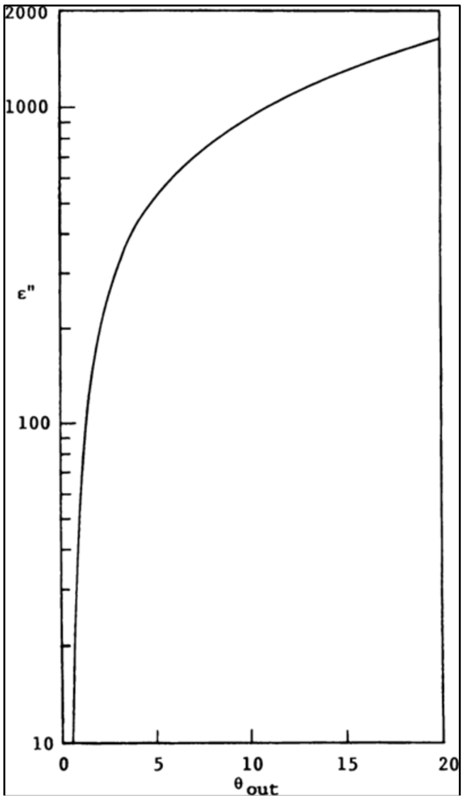

Fig 3: $\theta_{out}=-\theta_{in}$, $\Delta= 30°$.

Conclusion

Negative refraction can be caused by loss alone in a wedge, but the losses needed are large. Physics of parallel wires wires with split ring NIM media are more complex than originally thought, and their loss (due to reflection) may be large. The suggestions of Sanz *et al.* [3], that any attempt to demonstrate negative refraction should measure the exit beam peak shift in a slab from an incident Gaussian beam, thereby removing most of the loss versus angle problem, are reinforced.

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