Metamaterial Waveguide HOM Loads for SRF Accelerating Cavities

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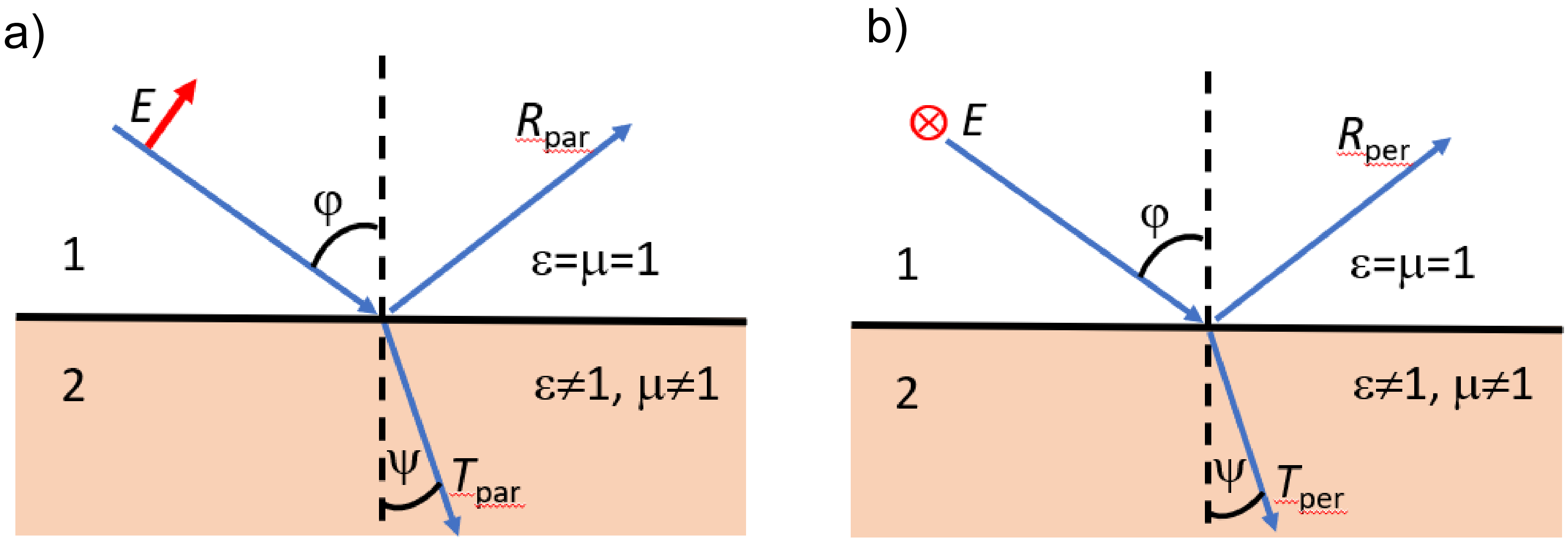
Suppression of beam induced HOMs is necessary for most SRF accelerating cavities driven with high currents. One of the problems in design of a HOM load is that vacuum compatible materials with high enough imaginary part of the dielectric permittivity, which provides absorption, have also a high real part of the permittivity. This does not allow absorbing RF radiation at short distance and in broad frequency band. We propose considering artificial metamaterials where besides lossy dielectric pieces, an absorber with high magnetic permeability is included. In our proposal, we suggest composing a waveguide HOM load of a metamaterial consisted of well-known ceramic and ferrite plates placed periodically in a stack. Such a design provides low return losses, compactness and broad frequency range of the operation.



Plane wave reflection and transmission diagram for parallel (a) and perpendicular (b) polarizations.

In the case of the so-called parallel polarization (Fig. 1a), the reflection coefficient is given by the equation [13]:

$$R_{par} = \frac{cos\varphi - \sqrt{\frac{\mu}{\varepsilon}}cos\psi}{cos\varphi + \sqrt{\frac{\mu}{\varepsilon}}cos\psi} \ , \tag{1}$$

where φ is the angle of incidence and ψ - is an angle of refraction given by:

$$\frac{sin\varphi}{sin\psi} = \sqrt{\varepsilon\mu} \ . \tag{2}$$

The numerator of the equation (1) equals zero if the following condition is satisfied:

$$\mu = \frac{\varepsilon^2 cos^2\varphi + sin^2\varphi}{\varepsilon} \ . \tag{3}$$

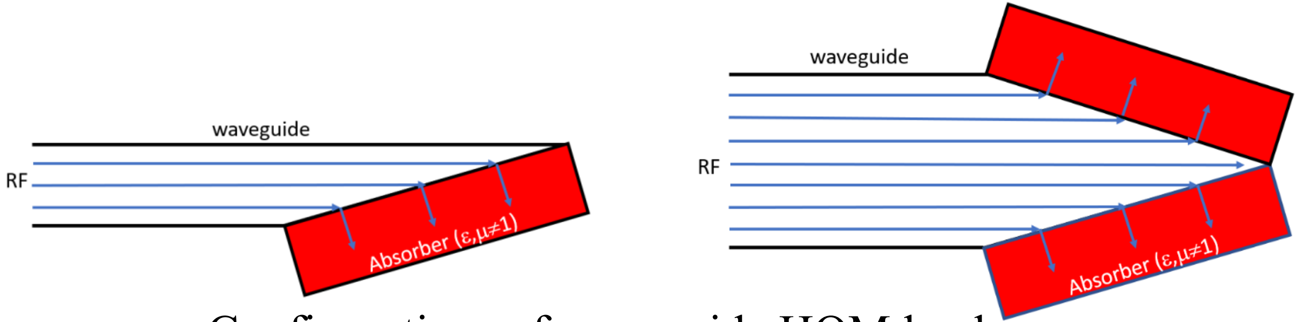
For the case of |ε|>>1, which is true for most ceramics, equation (2) takes a remarkably simple form:

$$\frac{\mu}{\varepsilon} = cos^2\varphi. \tag{4}$$

Because both ε and μ are assumed to have complex values, instead of (4) one can write two separate conditions that together are equivalent to equation (4):

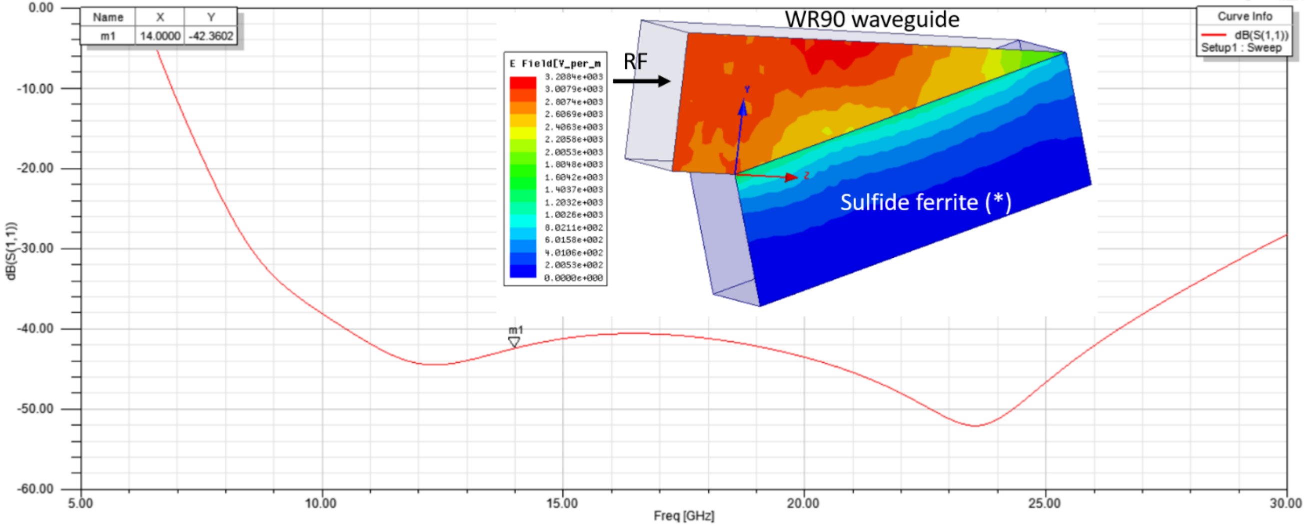
$$\frac{\mu'}{\varepsilon'} = cos^2\varphi, \tag{5a}$$

$$tan\delta_{\varepsilon} = tan\delta_{\mu}, \tag{5b}$$



Configurations of waveguide HOM loads.

A sulfide-based nanomaterial (MoS_2@FeCo) has $\varepsilon'=7.9$, $\tan\delta_\varepsilon=0.26$, $\mu'=0.95$, and $\tan\delta_\mu=0.25$ when measured at 14.4 GHz. In accordance with equation (5a), this material will provide good matching at the angle $\varphi=69.7°$.



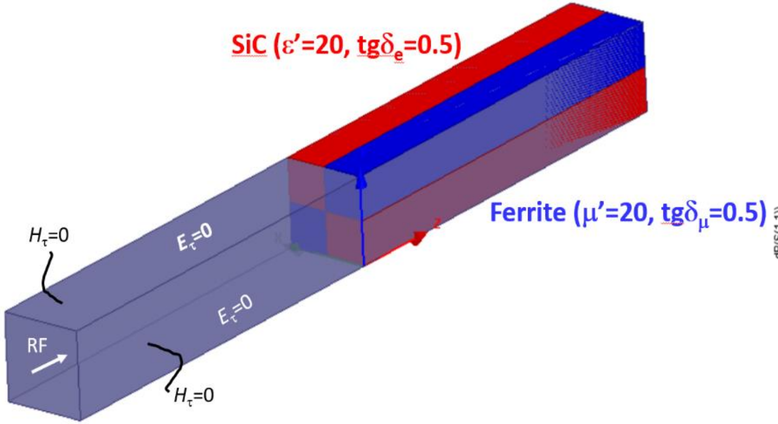
S_{11} (return loss) parameter vs frequency and field structure for a sulfide-based ferrite load (half of the full geometry is shown).

The average ε and μ of an artificial material consisting of several other sub-components can be written based on the natural assumption that each sub-component material contributes to the real and imaginary parts of ε and μ in proportion to its own volumetric fraction.

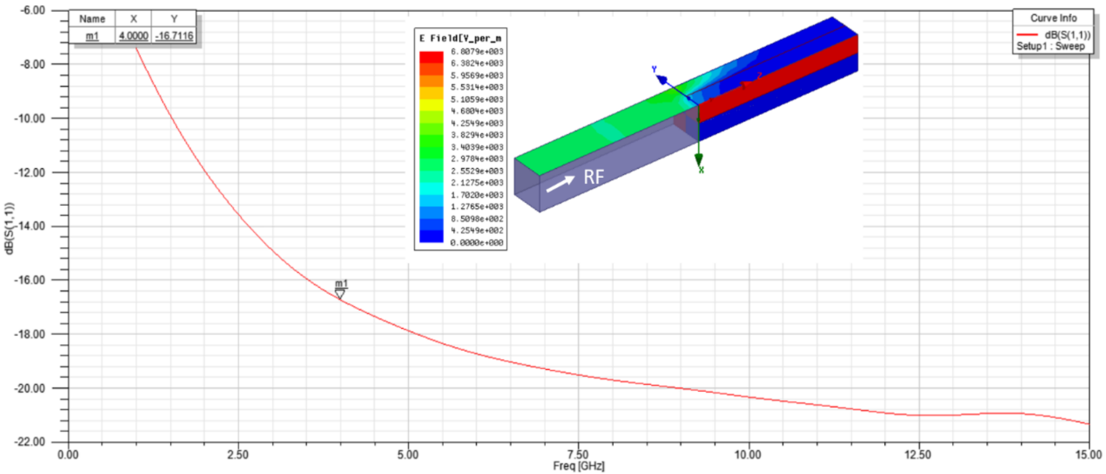
$$<\varepsilon' \geq \sum_i v_i \varepsilon_i', \quad <\varepsilon'' \geq \sum_i v_i \varepsilon_i'', \tag{8a}$$

$$<\mu' \geq \sum_i v_i \mu_i', \quad <\mu'' \geq \sum_i v_i \mu_i'', \tag{8b}$$

where v_i – is the fractional content of the i^{th} subcomponent material, and $\sum_i v_i = 1$.



Artificial medium composed of SiC- (red) and ferrite-like plates (blue).



S_{11} parameter vs frequency for the metamaterial composed of SiC- and ferrite-like plates.

a) Table 1: Material properties of lossy dielectric for HOM absorbers (ρ = density, CTE = coefficient of thermal expansion, κ = thermal conductivity, ε_r = relative permittivity, tan δ = loss tangent, σ = flexural strength).

Parameter	ρ	CTE (25-800°C)	κ	ε_r	tan δ	σ
Unit	g/cm^3	10^{-6}/°C	W/m•K			MPa
CEBAF AlN/GC [7]	3.0	4.7	55	20	> 0.1	300
Ceralloy 137 CA [5]	2.99	5.0	85	28[a] 18[b] 11[c]	0.2[a] 0.2[b] 0.2[c]	-
CoorsTek SC DS (SC-30) [9][11]	3.15	4.4	150	14[a] 11[b] 11[c] 12[d]	0.46[a] 0.18[b] 0.18[c] 0.15[d]	480
CoorsTek SC-DSG (SC-35) [9][11]	2.8	4.4	125	70[a] 37[b] 36[c] 33[d]	0.71[a] 0.58[b] 0.57[c] 0.57[d]	220
Sienna STL-100 AlN-SiC	3.26	5.1	115	38[b] 36[c] 33[d]	0.27[b] 0.33[c] 0.36[d]	590
Sienna STL-150D-X doped AlN	3.21	5.1	130	26[b] 26[c] 25[d]	0.69[b] 0.54[c] 0.53[d]	350

a = at 1 GHz, b = at 8 GHz, c = at 10 GHz, d = at 12 GHz

b)

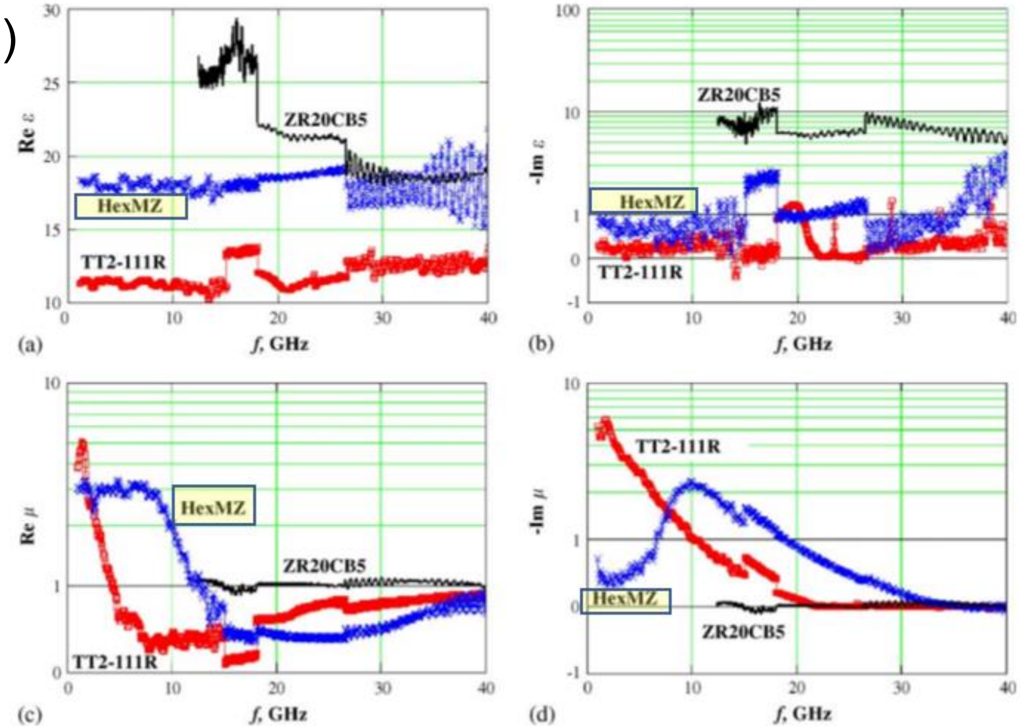


Fig.6. Parameters of ceramics from Ref. [1] (a), and the real and imaginary parts of ε and μ for ferrite materials from 1 to 40 GHz at 80 K from Ref. [2] (b).

1. Marhauser et al., presented at IPAC'11, San Sebastian, Sept. 2011, TUPS106, p. 1792 (2011); *http://www.JACoW.org.*

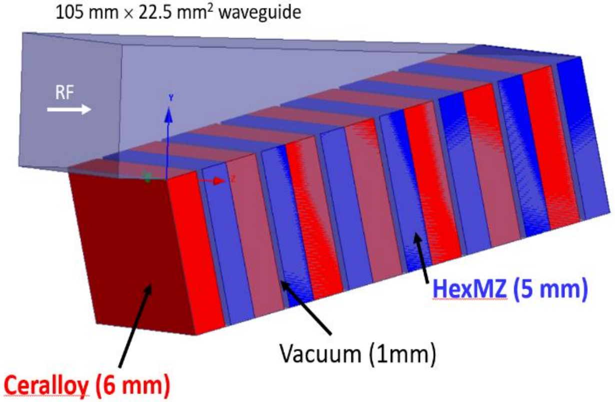
2. V. Shemelin, M. Liepe, H. Padamsee, Nuclear Instruments and Methods in Physics Research A 557 (2006) pp. 268–271.

Using the equations (8a) and (8b) and the conditions (5a) and (5b), one can easily generate several appealing material combinations. For example, we can have:

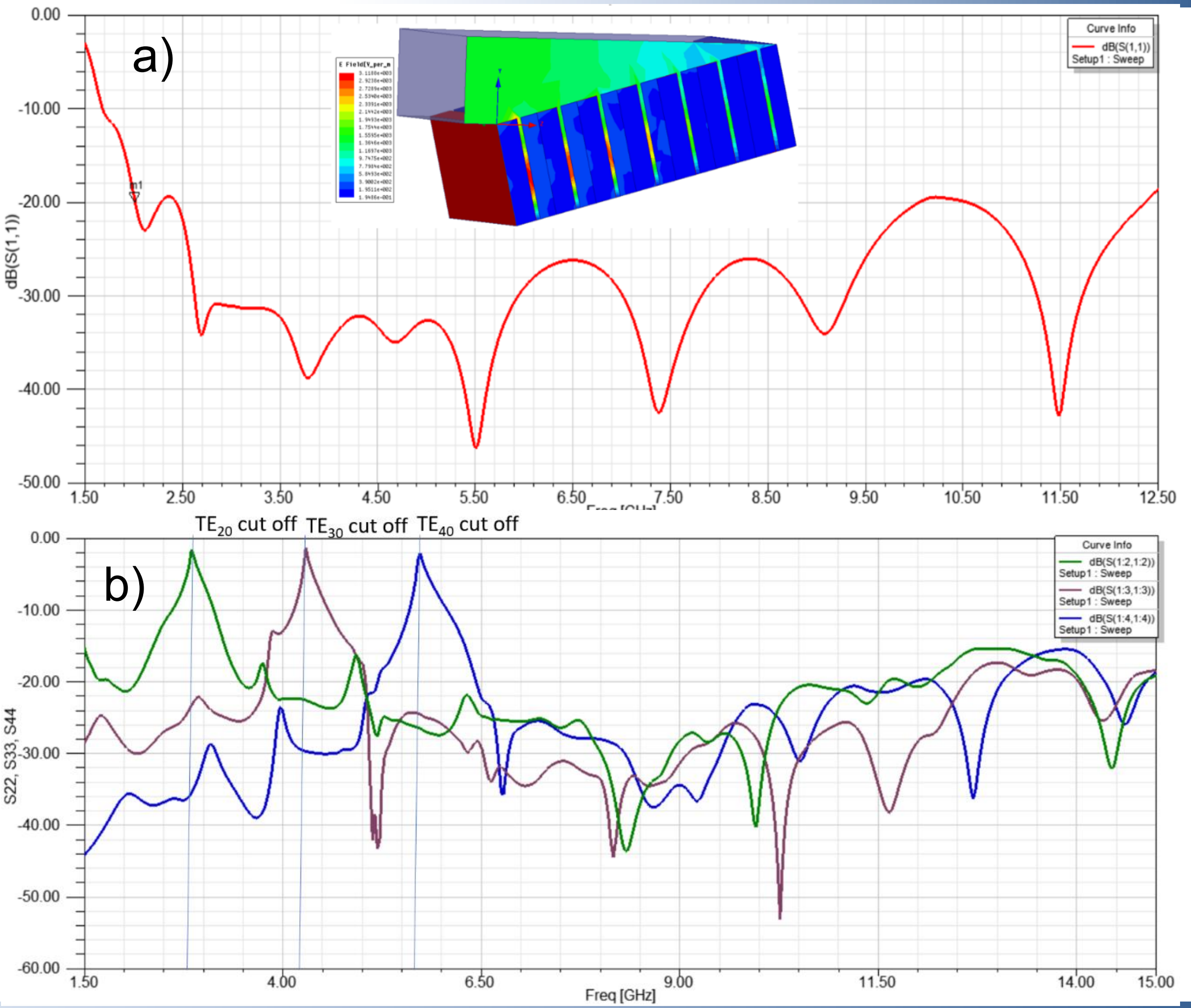
1) CoorsTek DS (SC-30) – 28.3% (ε'=14, tanδ_ε=0.46, μ'=1, tanδ_μ=0 at frequencies near 1 GHz from the Fig. 6a [1]),
   HexMZ – 49.5% (ε'=18, tanδ_ε=0.039, μ'=2, tanδ_μ=0.25 at frequencies up to 10 GHz from the Fig. 6b [2]),
   vacuum – 22.2%,
   -matched at the angle φ=70.3°;

2) CEBAF AIN/GC - 38.4% (ε'=20, tanδ_ε=0.1, μ'=1, tanδ_μ=0 from the Fig. 6a [1]),
   HexMZ – 20.2% (ε'=18, tanδ_ε=0.039, μ'=2, tanδ_μ=0.25 from the Fig. 6b [2]),
   vacuum – 41.4%,
   - matched at the angle φ=71.3°;

3) Ceralloy - 49% (ε'=28, tanδ_ε=0.2, μ'=1, tanδ_μ=0 at frequencies near 1 GHz from the Fig. 6a [1]) ,
   HexMZ – 40% (ε'=18, tanδ_ε=0.039, μ'=2, tanδ_μ=0.25 from the Fig. 6b [2]),
   vacuum – 11%,
   - matched at the angle φ=75.1°.



S-parameters vs frequency for a metamaterial load composed of Ceralloy and HexMZ plates, as well as vacuum gaps, with a realistic frequency-dependent ε and μ for both sub-materials: a – TE_{10} return loss, b – TE_{20} (green), TE_{30} (brown) and TE_{40} (blue) return losses. The field structure is shown at a frequency of 2 GHz.



Conclusion

New compact broadband HOM loads are proposed. They are assembled as a stack of ultrahigh vacuum compatible ceramic and ferrite plates, which are placed in a periodic order in a rectangular cross-section waveguide. In order to satisfy the best matching for the boundary between vacuum and the metamaterial, the parameters of this metamaterial, ε and μ, can be controlled by changing the content (percentage) of the mentioned sub-materials.