Mantle Cloaking Using Sub-Wavelength Conformal Metallic Meshes and Patches

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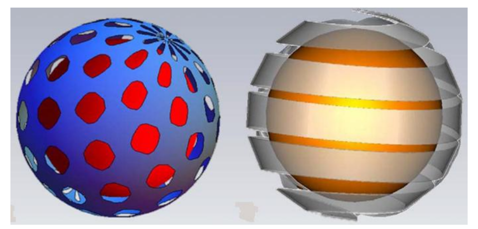
Background and Motivation

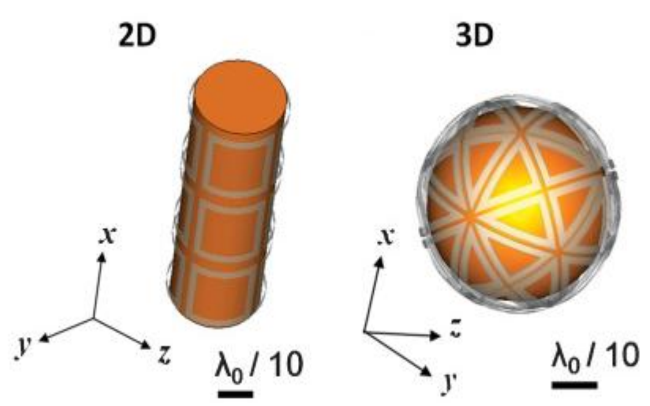
Mantle Cloak



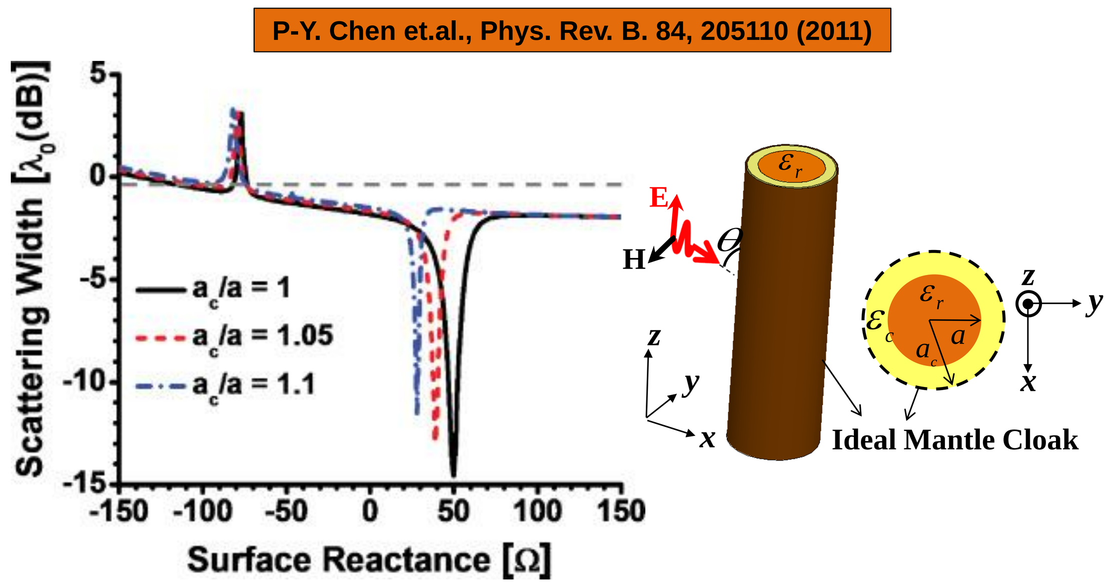
A. Alù, Phys. Rev. B. 80, 245115 (2009)

✓ Cloaking technique is based on scattering cancellation mechanism

FSS Mantle Cloaks

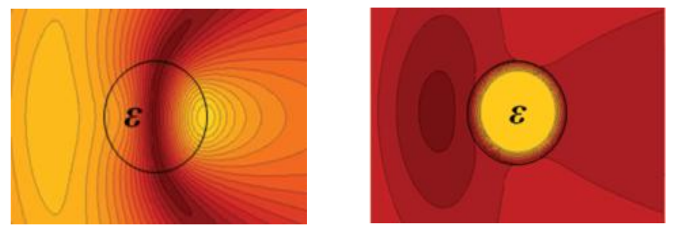


P-Y. Chen et.al., Phys. Rev. B. 84, 205110 (2011)



✓ The specific design of the metasurface has been carried out **by optimizing numerically** the shape and parameters of the metasurface elements

Electric field distributions



No Cloak **With Cloak**

Statement of the Problem

GOAL: SIMPLE AND EFFICIENT MODELING OF CYLINDRICAL FSS MANTLE CLOAKS

We are interested in the analysis of the scattering properties of the dielectric and conducting cylinders covered by printed (patches, Jerusalem crosses, and cross dipoles) and slotted arrays (meshes, slot-Jerusalem crosses, and slot-cross dipoles)

The analysis is based on **Lorenz-Mie scattering theory** which utilizes the **two-sided impedance boundary conditions** at the interface of the sub-wavelength elements

With the assumption that the unit-cell is much smaller than λ_0

The analytical grid-impedance expressions derived for the planar arrays of sub-wavelength elements may be successfully used to model and tailor the surface reactance of cylindrical conformal mantle cloaks

Theoretical Formulation

$$E = E_0 \sum_{n=-\infty}^{\infty} j^{-n}\left[J_n(k_0\rho) + c_n^{TM} H_n^{(2)}(k_0\rho)\right] e^{jn\phi}, \quad \rho \geq a_c,$$

$$E = E_0 \sum_{n=-\infty}^{\infty} j^{-n}\left[a_n^{TM} J_n(k_c\rho) + b_n^{TM} Y_n(k_c\rho)\right] e^{jn\phi}, \quad a \leq \rho \leq a_c,$$

$$E = E_0 \sum_{n=-\infty}^{\infty} j^{-n} d_n^{TM} J_n(k\rho) e^{jn\phi}, \quad \rho \leq a,$$

$k_0 = \omega\sqrt{\varepsilon_0\mu_0}$ $k_c = k_0\sqrt{\varepsilon_c}$ $k = k_0\sqrt{\varepsilon_r}$

J_n, Y_n are the Bessel functions of the first and second kind, and $H_n^{(2)}$ is the Hankel function of the second kind

Unknown Coefficients: a_n^{TM}, b_n^{TM}, c_n^{TM}, d_n^{TM}

Boundary Conditions:

✓ continuity of tangential components of electric and magnetic fields at the boundary of the core ($\rho = a$)

✓ *two-sided impedance boundary conditions* at the interface of the mantle cloak ($\rho = ac$)

$$E_t|_{\rho=a_c^+} = E_t|_{\rho=a_c^-} = Z_s(H_t|_{\rho=a_c^+} - H_t|_{\rho=a_c^-})$$

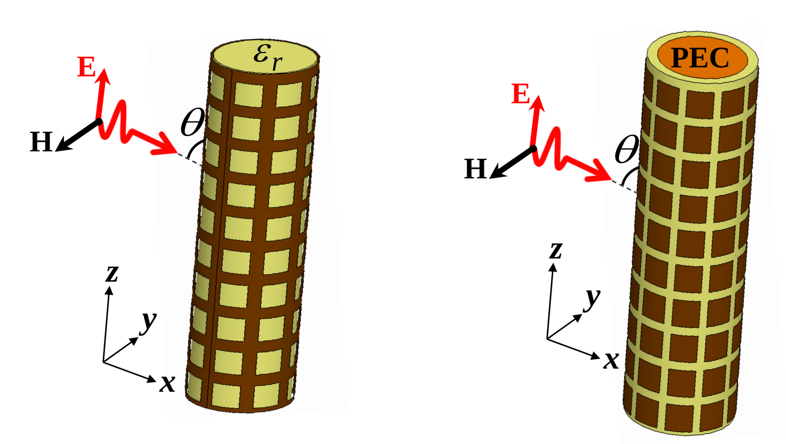
Z_s is the surface impedance of the FSS mantle cloaks

$Z_s = R_s + jX_s$ ➡ For lossless case (Rs = 0), $Z_s = jX_s$

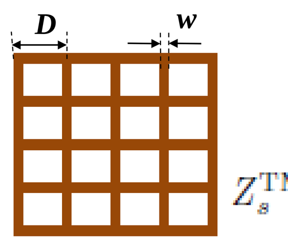
Scattering Width

$$\sigma_s = \frac{4}{k_0}\left|\sum_{n=-\infty}^{\infty} c_n^{TM}\right|^2$$

Analytical Grid Impedance Expressions



Meshes **Patches**

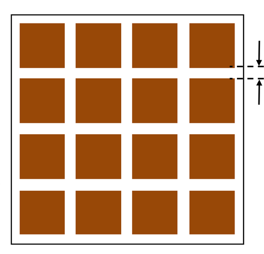


$$Z_s^{TE,Mesh} = \frac{j\omega\eta_0 D}{2c\pi}\ln\csc\left(\frac{\pi w}{2D}\right)$$

$$Z_s^{TM,Mesh} = \frac{j\omega\eta_0 D}{2c\pi}\ln\csc\left(\frac{\pi w}{2D}\right)\left(1 - \frac{\sin^2\theta_s}{\varepsilon_r + 1}\right)$$

where $\theta_s = 90° - \theta$

O. Luukkonen, et.al., *IEEE Trans. Antennas Propag.*, Vol. 56, No. 6, pp. 1624-1632, June 2008

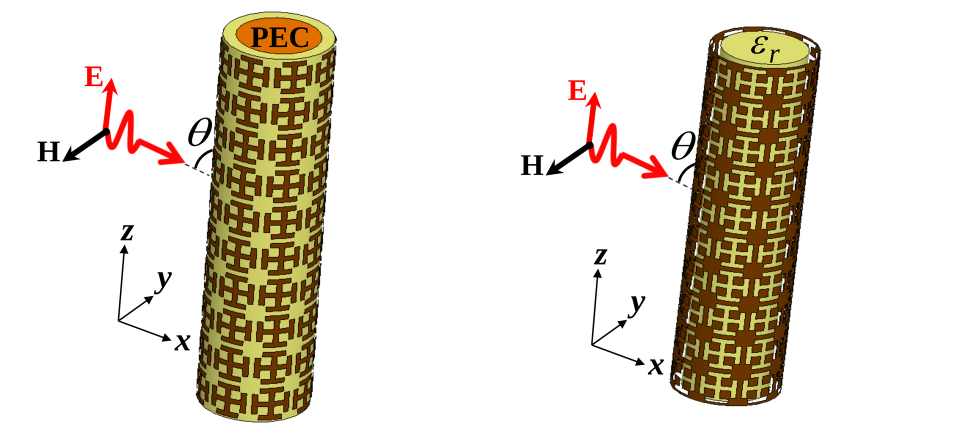


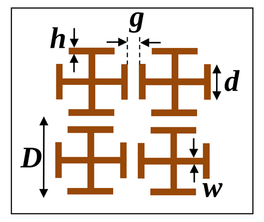
Babinet's Pricinple $Z_s^{TE} Z_s^{TM'} = \frac{\eta_0^2}{2(\varepsilon_r + 1)}$

$$Z_s^{TM,Patch} = \frac{\eta_0^2}{2(\varepsilon_r + 1) Z_s^{TE,Mesh}}$$

$$Z_s^{TE,Patch} = \frac{\eta_0^2}{2(\varepsilon_r + 1) Z_s^{TM,Mesh}}$$

Printed Jerusalem Crosses / Slot-Jerusalem Crosses





$$Z_s^{TM,JC} = j\omega L_g^{TM} + \frac{1}{j\omega C_g}$$

$$Z_s^{TE,JC} = j\omega L_g^{TE} + \frac{1}{j\omega C_g}$$

$$L_g^{TE} = \frac{\eta_0 D}{2c\pi}\ln\csc\left(\frac{\pi w}{2D}\right)\left(1 - 2\frac{\sin^2\theta_s}{\varepsilon_r + 1}\right)$$

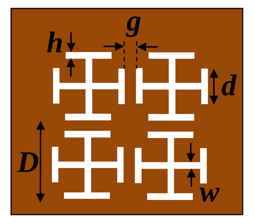
$$L_g^{TM} = \frac{\eta_0 D}{2c\pi}\ln\csc\left(\frac{\pi w}{2D}\right)$$

$$C_g = \frac{\varepsilon_0\varepsilon_r d}{\pi}\left[\ln\csc\left(\frac{\pi g}{2D}\right) + F\right]$$

$$F = \frac{\sqrt{1 - \left(\frac{d}{\lambda}\right)^2} u^2}{1 + \sqrt{1 - \left(\frac{d}{\lambda}\right)^2}(1-u)^2} + \left[\frac{du(3u-2)}{4\lambda}\right]^2$$

$$u = \cos^2\left(\frac{\pi g}{2d}\right) \quad \lambda = \frac{2\pi}{k_0\sqrt{\left(\frac{\varepsilon_r + 1}{2}\right)}}$$

C. R. Simovski, et.al., *IEEE Trans. Antennas Propag.*, Vol. 53, no. 3, pp. 908-914, Mar. 2005

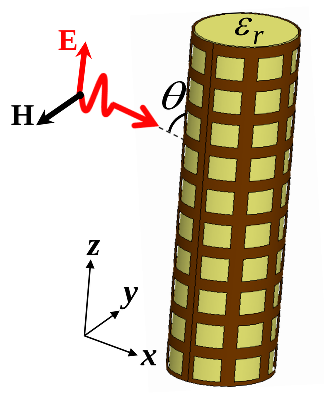


Babinet's Pricinple $Z_s^{TE} Z_s^{TM'} = \frac{\eta_0^2}{2(\varepsilon_r + 1)}$

$$Z_s^{TM,Slot\ JC} = \frac{\eta_0^2}{2(\varepsilon_r + 1) Z_s^{TE,JC}}$$

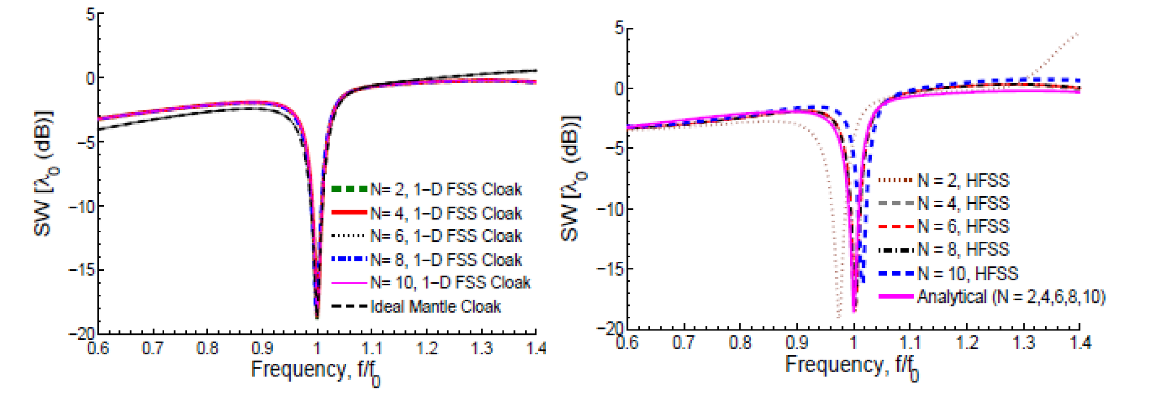
$$Z_s^{TE,Slot\ JC} = \frac{\eta_0^2}{2(\varepsilon_r + 1) Z_s^{TM,JC}}$$

Dielectric Cylinder: Slotted FSS Cloaks

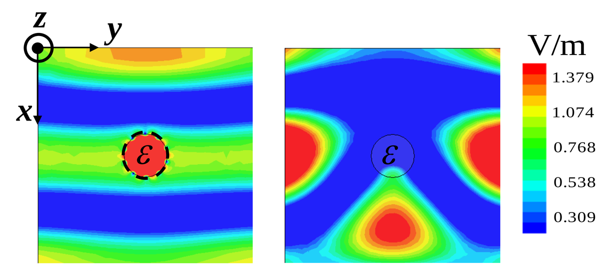


$a = \frac{\lambda_0}{10}, \varepsilon_r = 10$ $a_c = a, \varepsilon_c = 1$ $N = \frac{2\pi a}{D}$

N	D	w	ε_r	$a_c = a$
2	$\lambda_0/3$	$\lambda_0/7$	10	$\lambda_0/10$
4	$\lambda_0/6$	$\lambda_0/6$	10	$\lambda_0/10$
6	$\lambda_0/10$	$\lambda_0/10$	10	$\lambda_0/10$
8	$\lambda_0/13$	$\lambda_0/125$	10	$\lambda_0/10$
10	$\lambda_0/16$	$\lambda_0/200$	10	$\lambda_0/10$

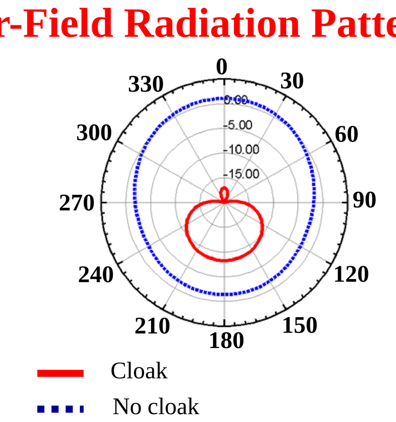


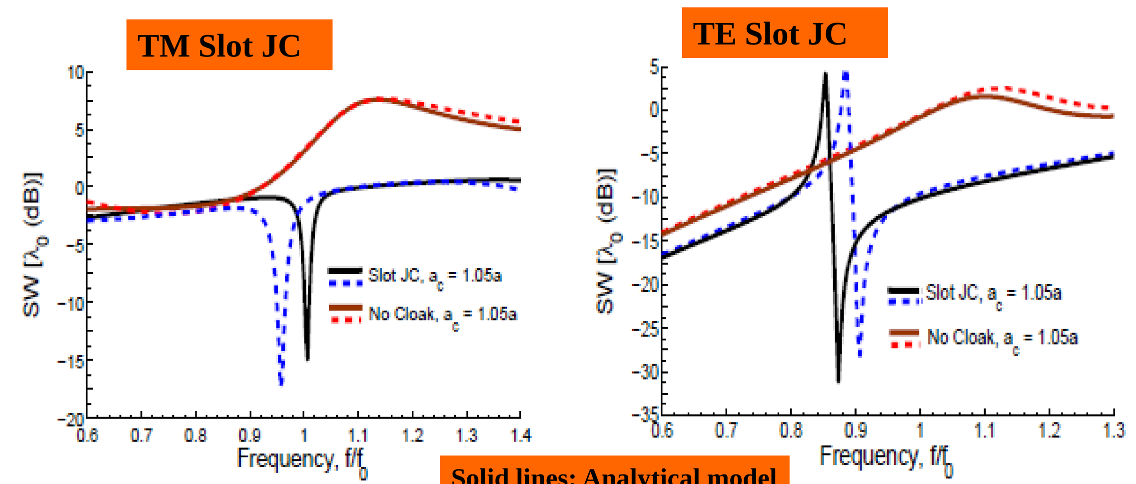
Electric field distributions



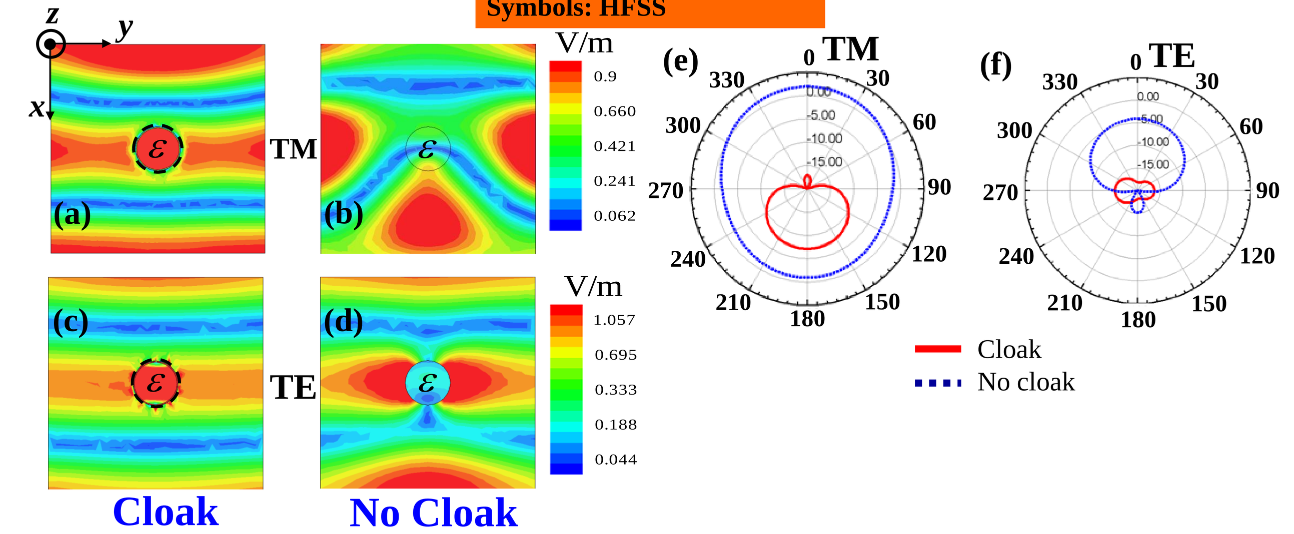
With Cloak **No Cloak**

Far-Field Radiation Patterns



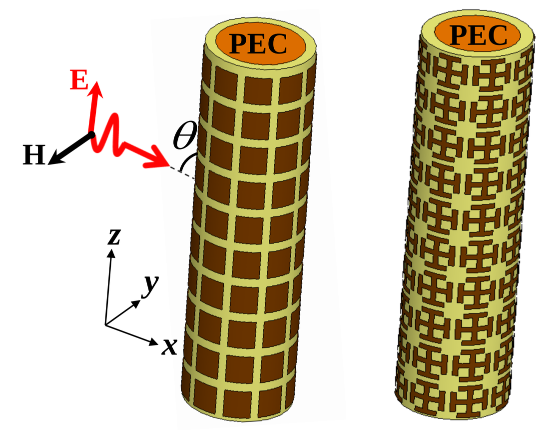


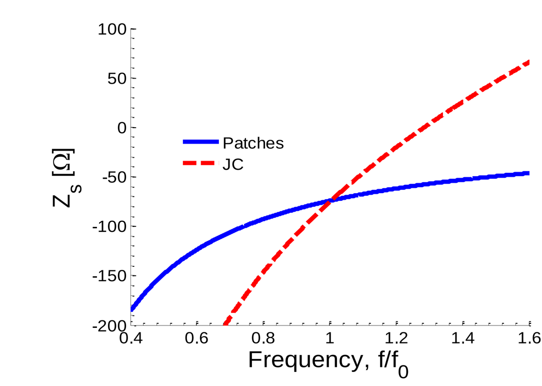
Solid lines: Analytical model
Symbols: HFSS



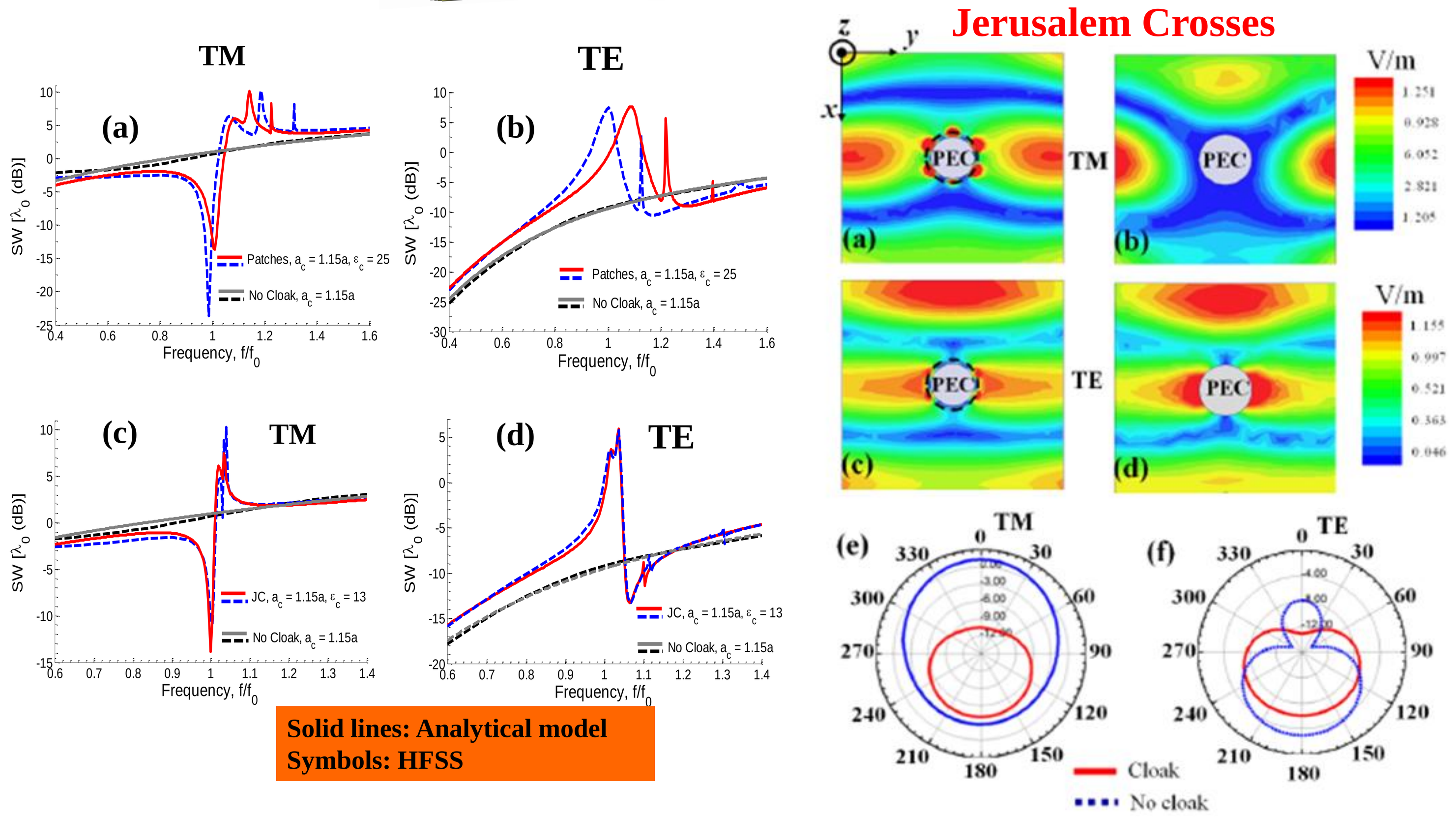
Cloak **No Cloak**

Conducting Cylinder: Printed FSS Cloaks





Jerusalem Crosses



Solid lines: Analytical model
Symbols: HFSS

Conclusion

- An analytical model is presented to suppress the scattering from the dielectric and conducting cylinders for both polarizations using various sub-wavelength periodic surfaces
- It has been shown that, in the presence of a simple conformal mantle cloak, the scattering from cylindrical rods may be significantly reduced and analytical formulas to derive the required surface reactance of the conformal surface may be borrowed from the established models for planar FSS
- All the results have been validated using **full-wave numerical simulations**
- Our results may greatly facilitate the implementation and design of mantle cloaks in a variety of applications, including **camouflaging and invisibility**, **cloaked sensing**, **non-invasive probing**, and **lowinterference communications**