Transformation Optics and Applications.

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Principes

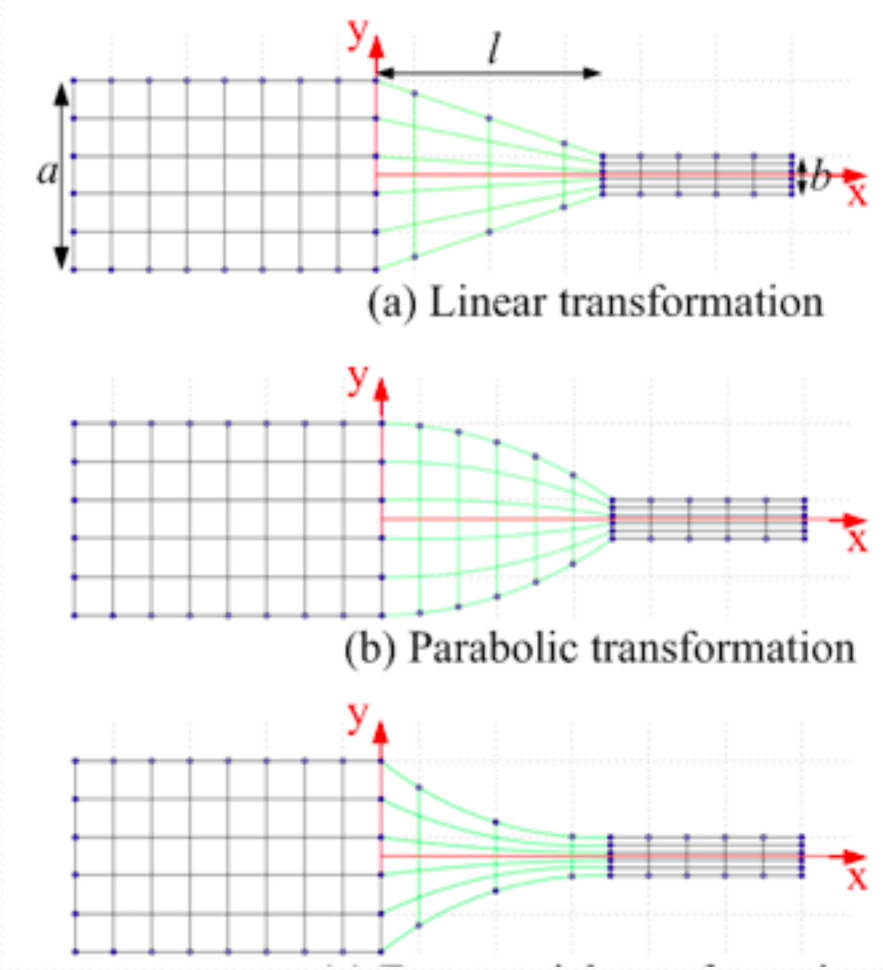
- On définit la relation analytique entre un espace de départ et un espace d'arrivée.
- *X'=f(x,y,z); Y'=g(x,y,z); Z'=h(x,y,z).*
- À partir de cette relation analytique on calcule la matrice du Jacobien de la transformation.
- On en déduit les expressions des tenseurs de permittivité et de perméabilité.

$$\varepsilon^{i'j'} = \frac{J_i^{i'} J_j^{j'} \varepsilon_0 \delta^{ij}}{\det(J)} \quad \text{and} \quad \mu^{i'j'} = \frac{J_i^{i'} J_j^{j'} \mu_0 \delta^{ij}}{\det(J)} \quad \text{with} \qquad J_\alpha^{\alpha'} = \frac{\partial x'^\alpha}{\partial x^\alpha}$$

- Problème: les valeurs sont souvent inexploitables.
- Solutions: on modifie la relation analytique.

Exemple: adaptateur de guide

- On veut relier deux guides de tailles différentes.
- 3 profils sont possibles: linéaire, parabolique, exponentiel.



(c) Exponential transformation

Transformation

$$\begin{cases} x' = x \\ y' = y\left(\dfrac{b-a}{2l}x + \dfrac{a}{2}\right) \\ z' = z \end{cases}$$

linéaire

$$\bar{\bar{\varepsilon}} = \bar{\bar{\theta}}\varepsilon_0 \qquad \bar{\bar{\mu}} = \bar{\bar{\theta}}\mu_0 \qquad \frac{J_i^{i'} J_j^{j'} \delta^{ij}}{\det(J)} = \theta^{i'j'}$$

$$\begin{cases} x' = x \\ y' = y\left(\dfrac{b-a}{2l^2}x^2 + \dfrac{a}{2}\right) \\ z' = z \end{cases}$$

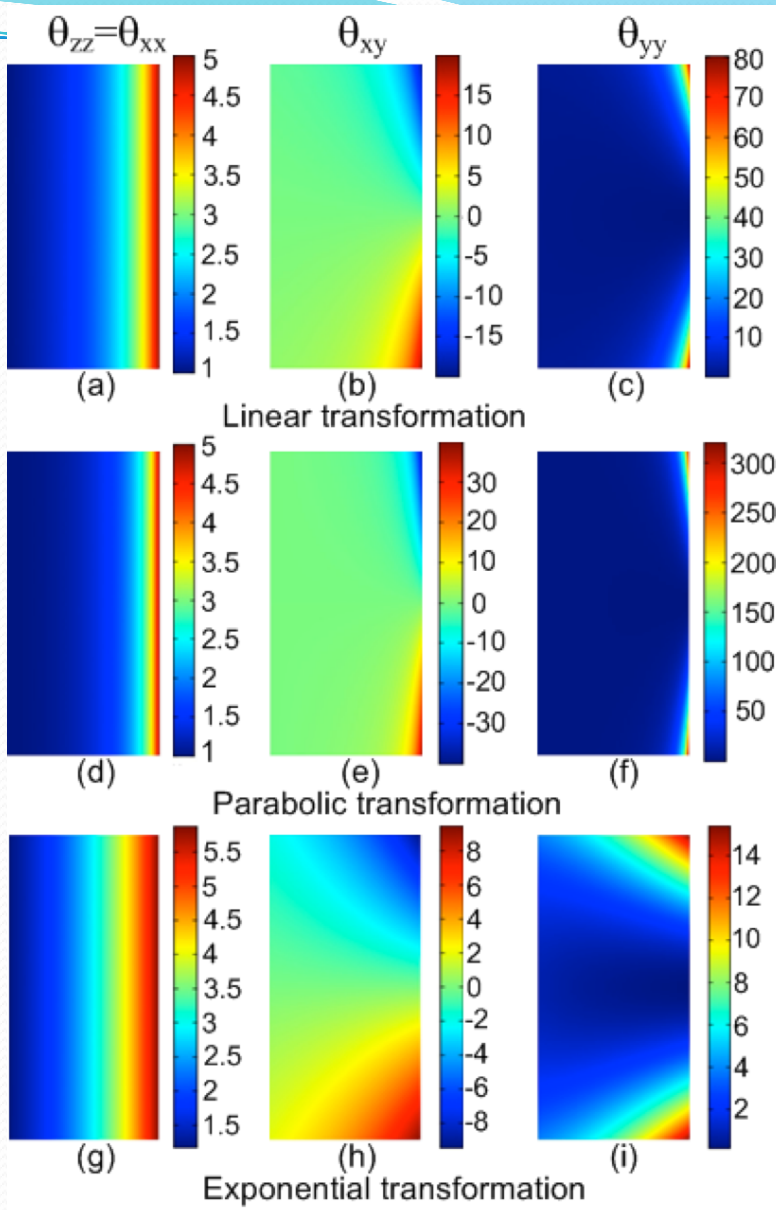
parabolique

$$\bar{\bar{\theta}} = \begin{pmatrix} \theta_{xx}(x') & \theta_{xy}(x',y') & 0 \\ \theta_{xy}(x',y') & \theta_{yy}(x',y') & 0 \\ 0 & 0 & \theta_{zz}(x') \end{pmatrix}$$

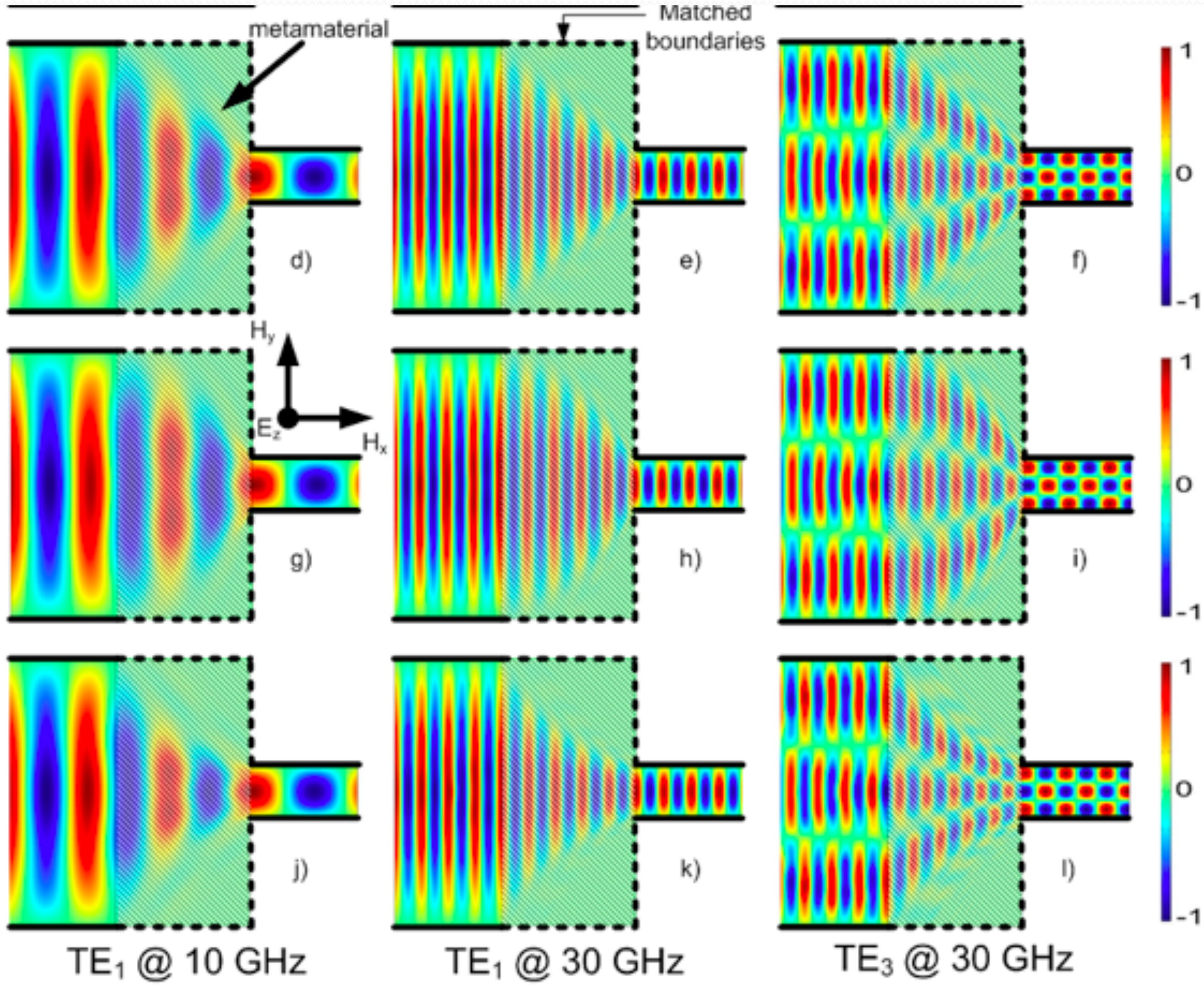
$$\begin{cases} x' = x \\ y' = y\left(\dfrac{b}{a}\right)^{\frac{x}{l}} \\ z' = z \end{cases}$$

exponentiel

Résultats et comparaisons: le profil exponentiel conduit aux valeurs les plus faibles.



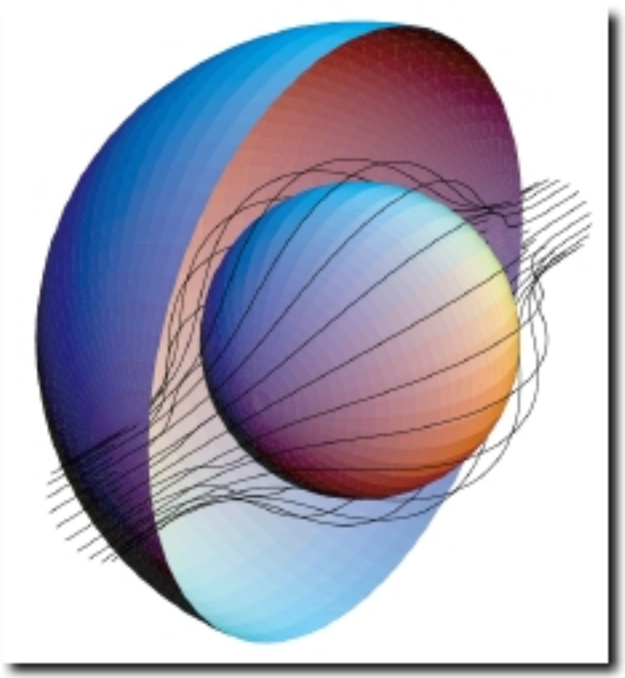
Simulations (pour vérifier!)



Et maintenant la réalisation!

1er Exemple: Invisibilité.

Invisibilité?



- En 2006 U. Leonhard et J.B. Pendry propose le concept d'invisibilité basé sur le principe de l'effet mirage.
- Cette invisibilité est basée sur la déviation des rayons lumineux par un milieu d'indice variable.
- D.R. Smith réalise un premier prototype en micro-onde fonctionnant à 8,5GHz.

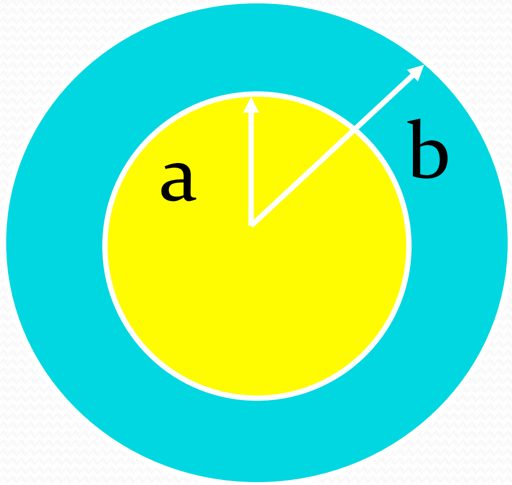
Invisibilité: le modèle…

$$r' = \frac{b-a}{b} r + a \quad \theta' = \theta \quad z' = z \qquad (1)$$

$$\varepsilon_r = \mu_r = \frac{r-a}{r} \quad \varepsilon_\theta = \mu_\theta = \frac{r}{r-a}$$

$$\varepsilon_z = \mu_z = \left(\frac{b}{b-a}\right)^2 \frac{r-a}{r} \qquad (2)$$

$$\varepsilon_z = \left(\frac{b}{b-a}\right)^2 \quad \mu_r = \left(\frac{r-a}{r}\right)^2 \quad \mu_\theta = 1 \qquad (3)$$

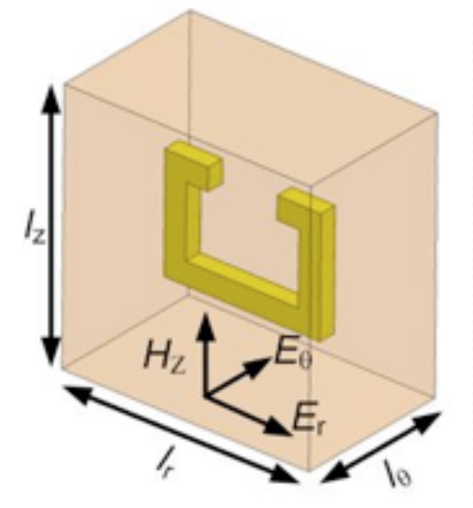


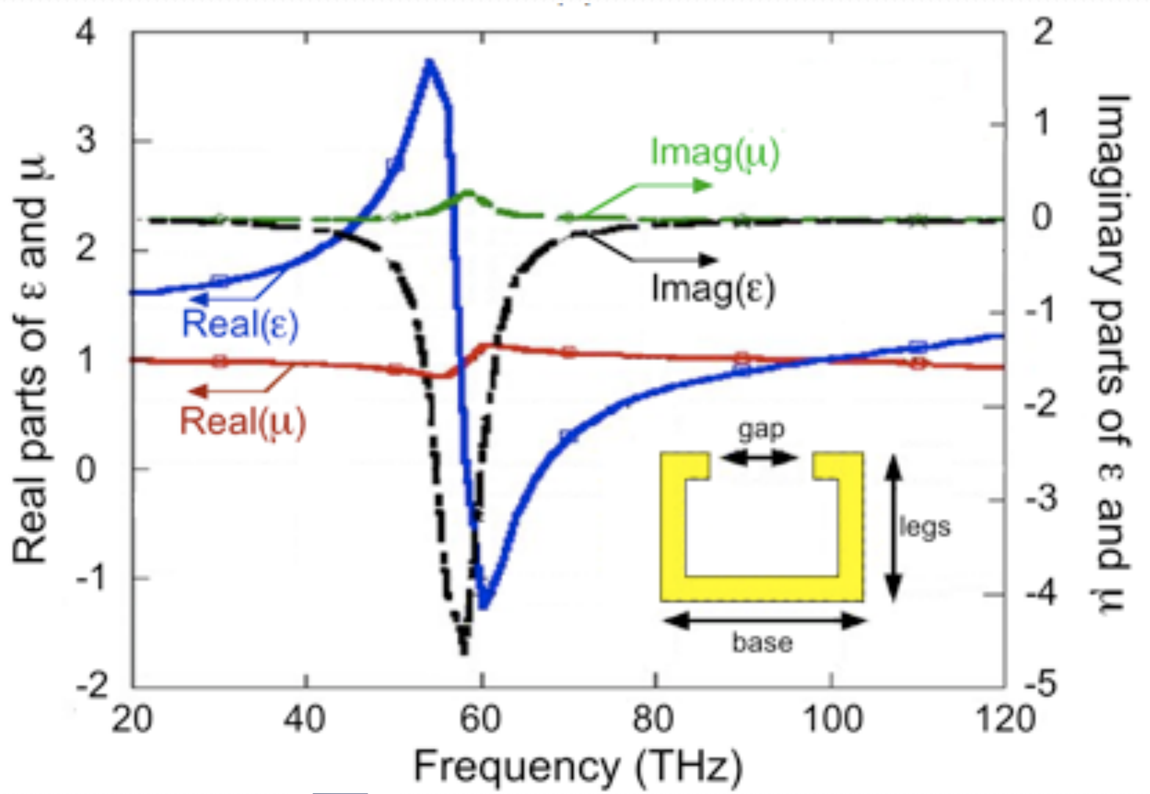
- La transformation est définie par (1). L'adaptation d'impédance est réalisée.
- Les paramètres du matériau par (2).
- Le modèle réduit est défini par (3). L'adaptation d'impédance n'est plus conservée.

IEF cloak:

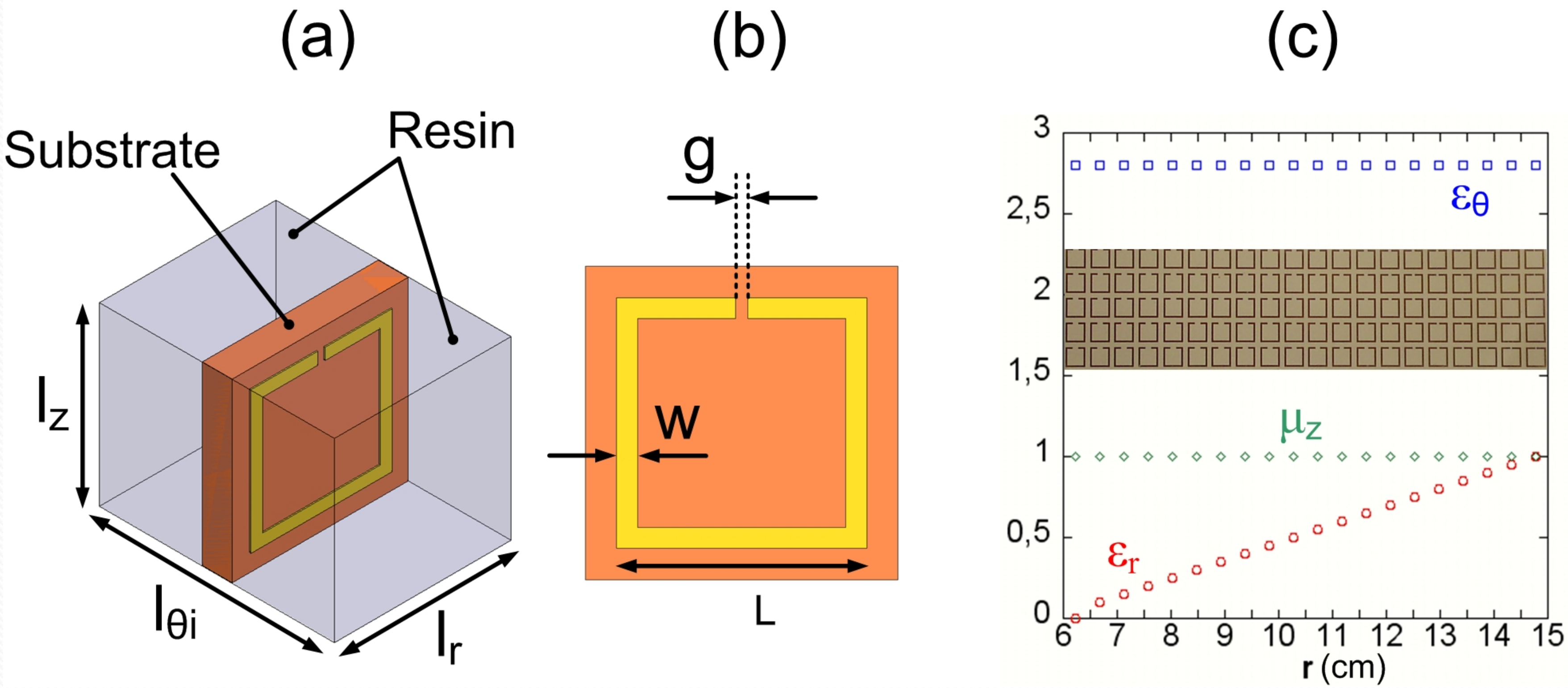
Material: Pendry's SRR electrical resonance

$$\mu_z = 1, \quad \varepsilon_\theta = \left(\frac{b}{b-a}\right)^2, \quad \varepsilon_r = \left(\frac{b}{b-a}\right)^2 \left(\frac{r-a}{r}\right)^2$$





Démonstration expérimentale d'une cape d'invisibilité non-magnétique



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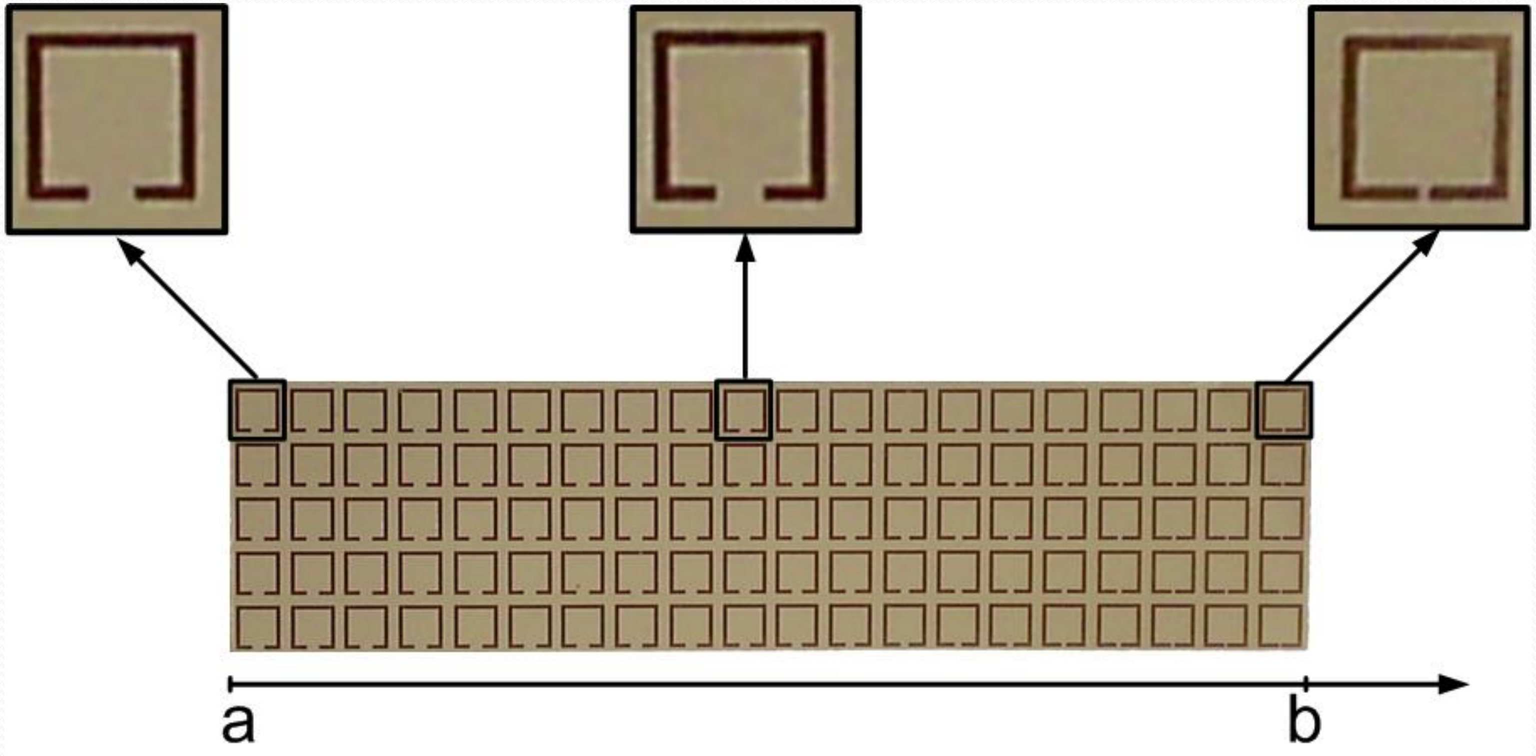
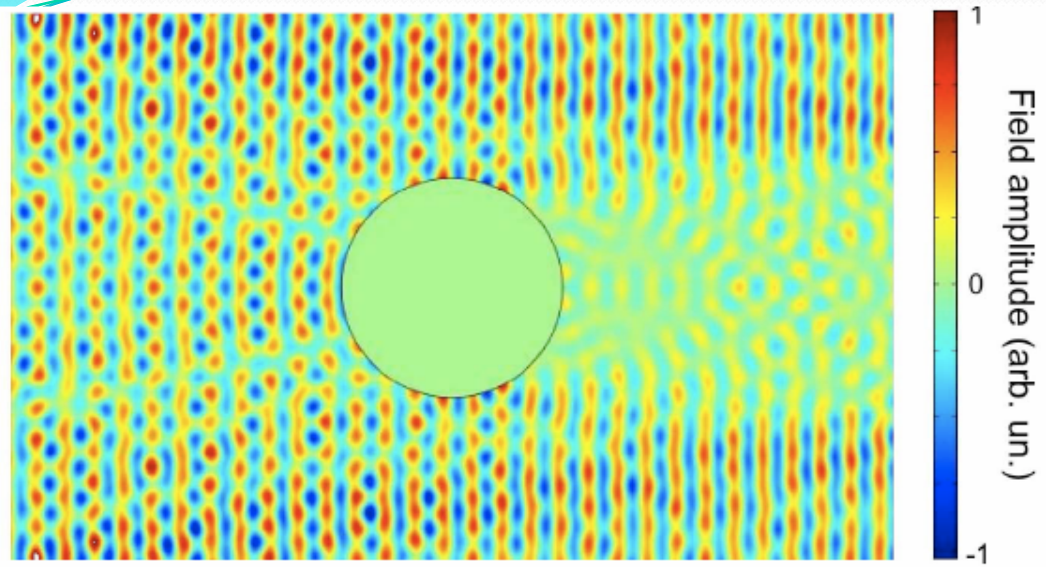


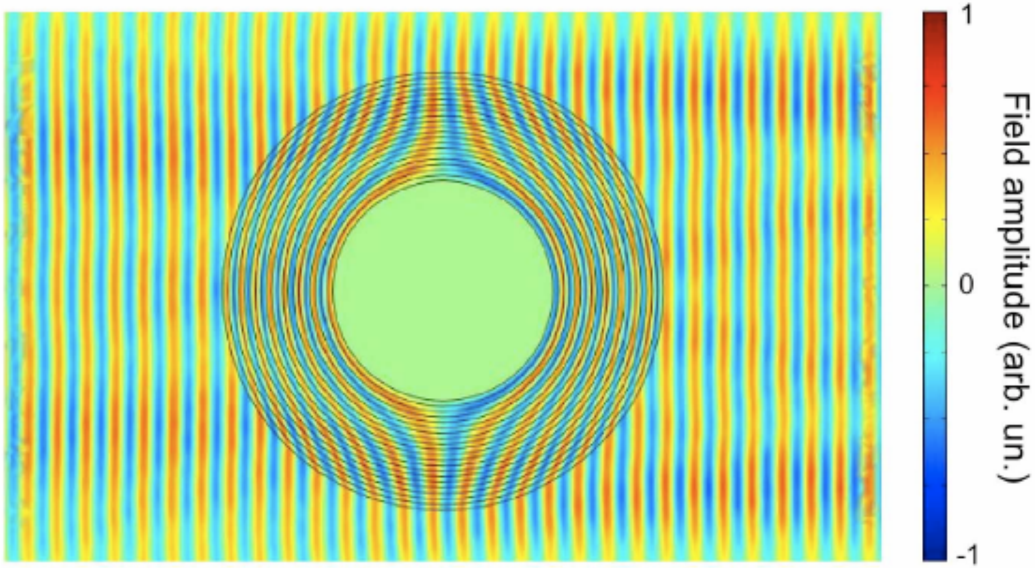
Conception simplifiée avec la coupure de l'anneau comme seul paramètre variable!

Simulations…

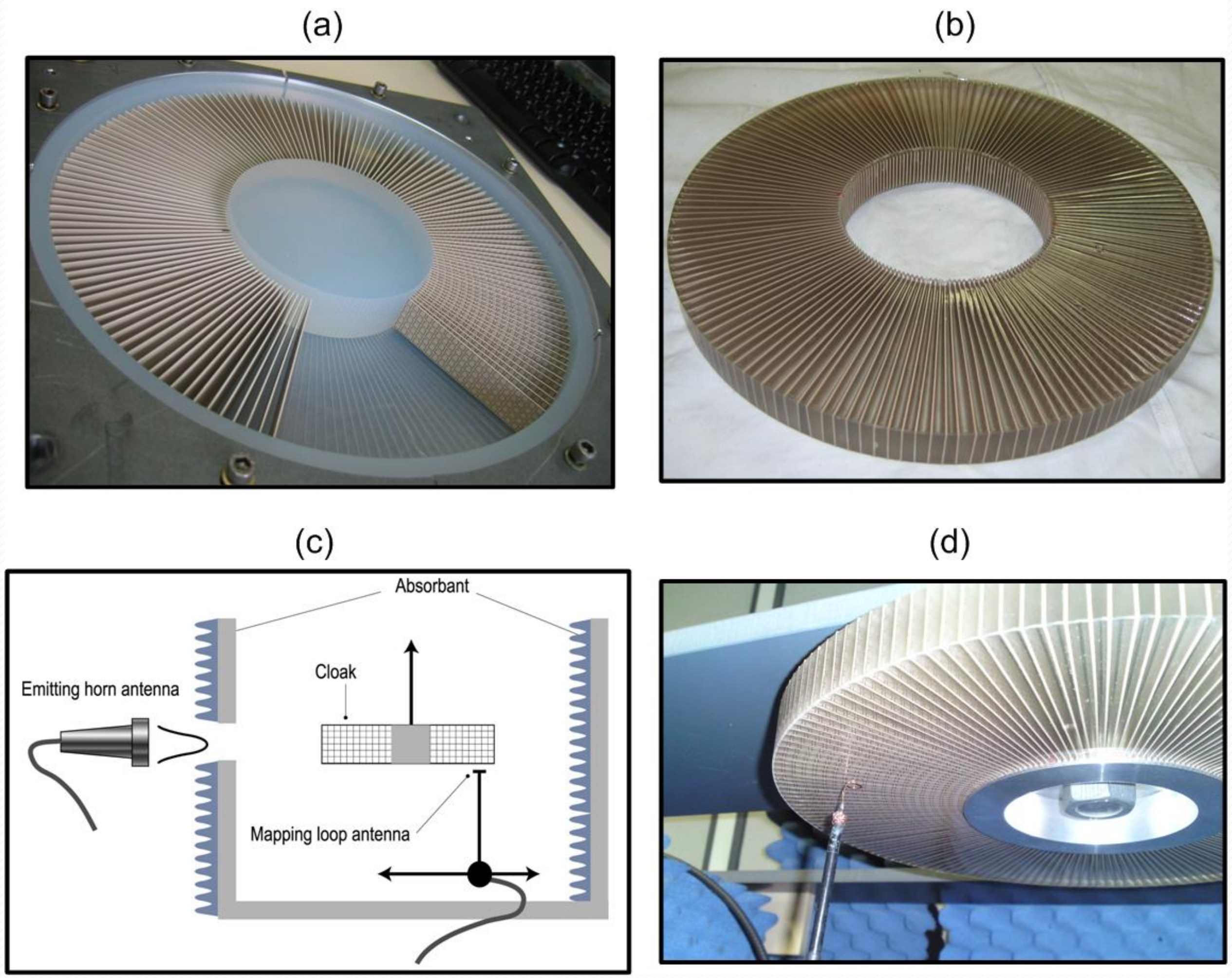


- Metallic cylinder without cloak.

✦Metallic cylinder with cloak.

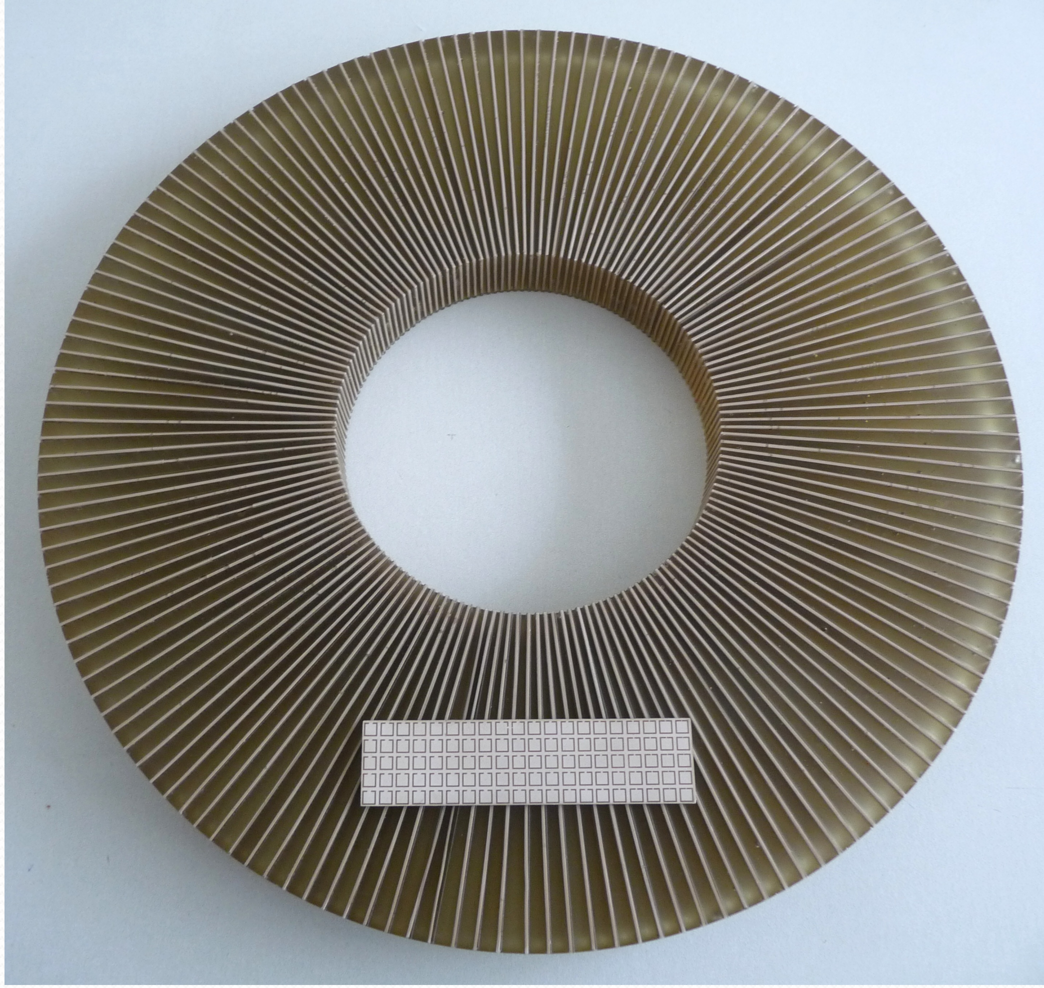


Réalisation et caractérisation



~32000 résonateurs

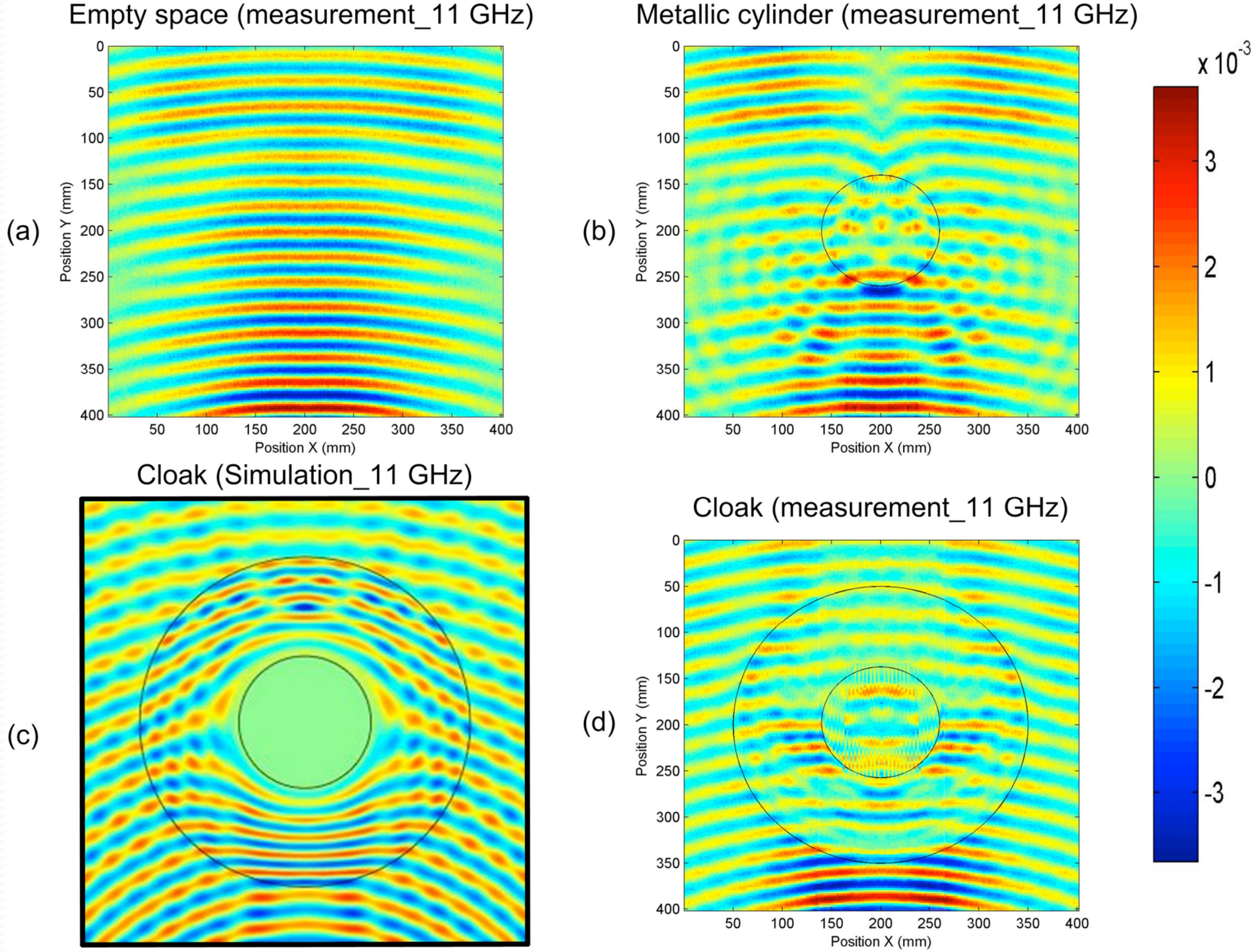
Realization…



	Kante *et al.* 11 GHz	Schurig *et al.* 8.5 GHz
a	6 cm $2a \sim 4.4\lambda_0$	2.71 cm $2a \sim 1.5\lambda_0$
b	15 cm	5.89 cm

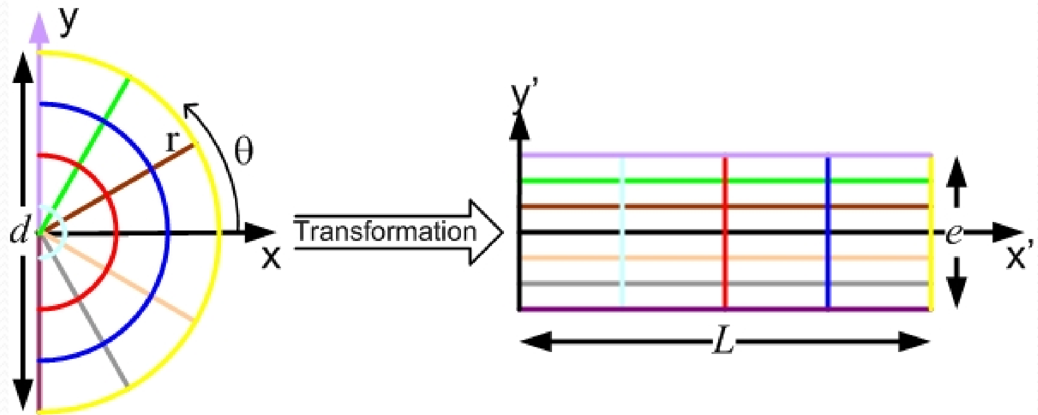
- Working frequency 11GHz.

Measurements.



2ème exemple: Antenne directive.

Coordinate transformation and directive antenna (IEF).



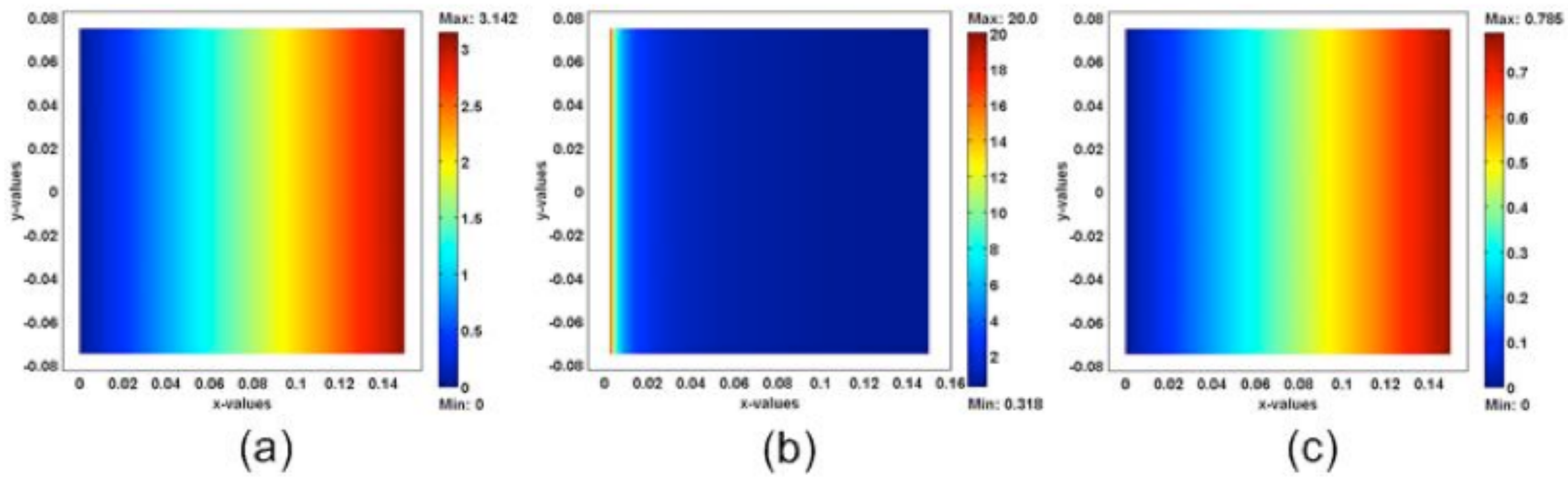
$$\begin{cases} x' = \dfrac{2L}{d}\sqrt{x^2 + y^2} \\ y' = \dfrac{e}{\pi}\arctan\left(\dfrac{y}{x}\right) \\ z' = z \end{cases}$$

$$\bar{\bar{\varepsilon}} = \begin{pmatrix} \varepsilon_{xx}(x',y') & 0 & 0 \\ 0 & \varepsilon_{yy}(x',y') & 0 \\ 0 & 0 & \varepsilon_{zz}(x',y') \end{pmatrix} \varepsilon_0 \qquad \bar{\bar{\mu}} = \begin{pmatrix} \mu_{xx}(x',y') & 0 & 0 \\ 0 & \mu_{yy}(x',y') & 0 \\ 0 & 0 & \mu_{zz}(x',y') \end{pmatrix} \mu_0$$

$$\varepsilon_{xx}(x',y') = \mu_{xx}(x',y') = \frac{\pi}{e}x' \qquad \varepsilon_{yy}(x',y') = \mu_{yy}(x',y') = \frac{1}{\varepsilon_{xx}(x',y')} \qquad \varepsilon_{zz} = \mu_{zz} = \frac{d^2\pi}{4eL^2}x'$$

- Transformation of an isotropic antenna to a directive one.

Calculated permittivities and permeabilities.

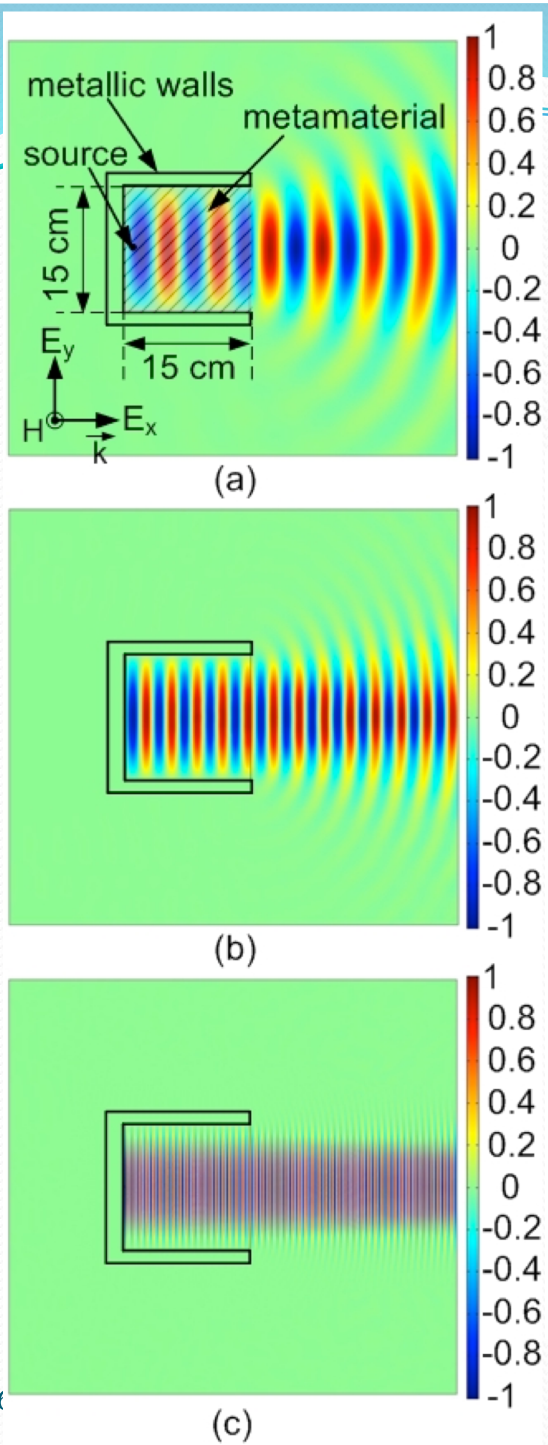


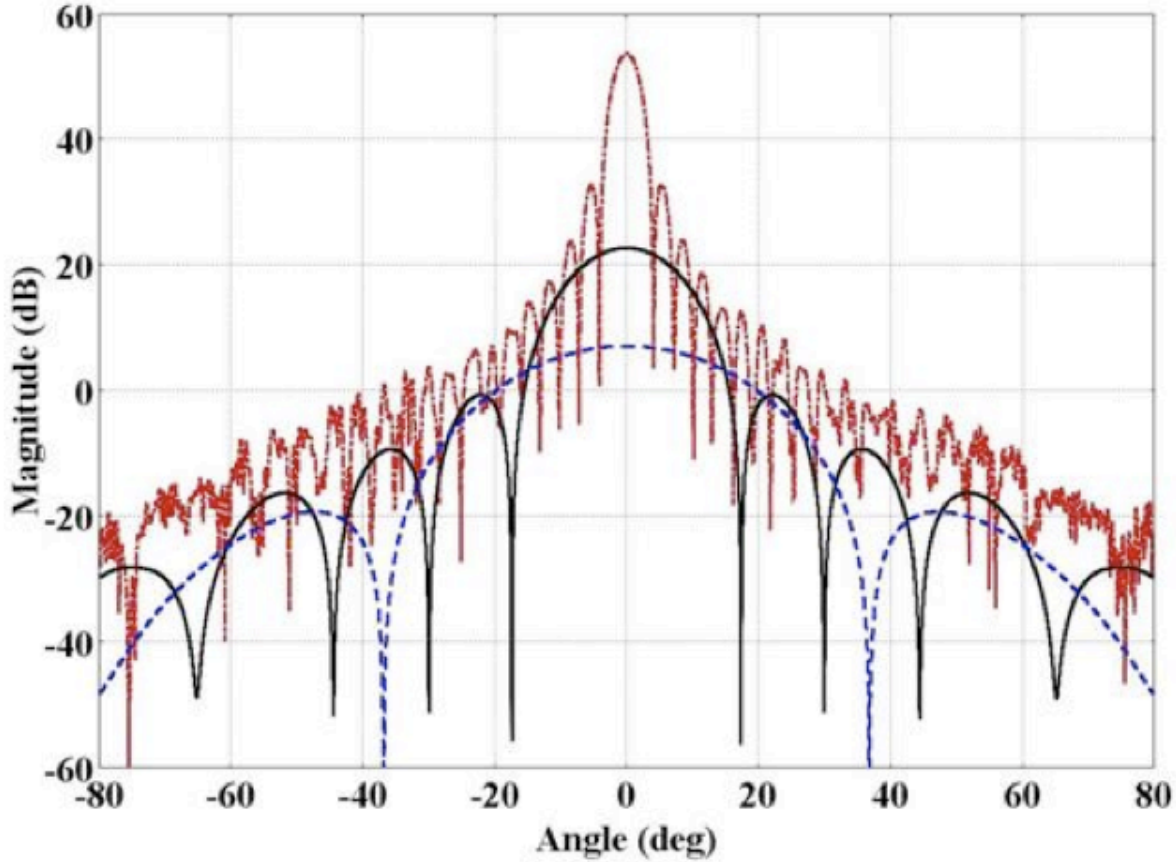
$$\overline{\overline{\varepsilon}} = \begin{pmatrix} \varepsilon_{xx}(x',y') & 0 & 0 \\ 0 & \varepsilon_{yy}(x',y') & 0 \\ 0 & 0 & \varepsilon_{zz}(x',y') \end{pmatrix} \varepsilon_0$$

Variation of the permittivity tensor components: (a) ε_{xx}, (b) ε_{yy} , and (c) ε_{zz}.

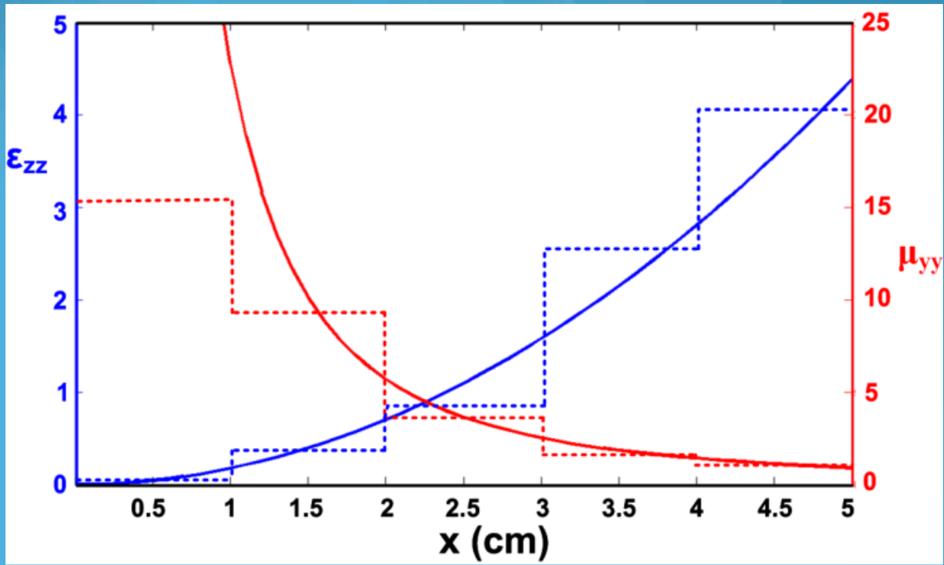
2D Simulations…

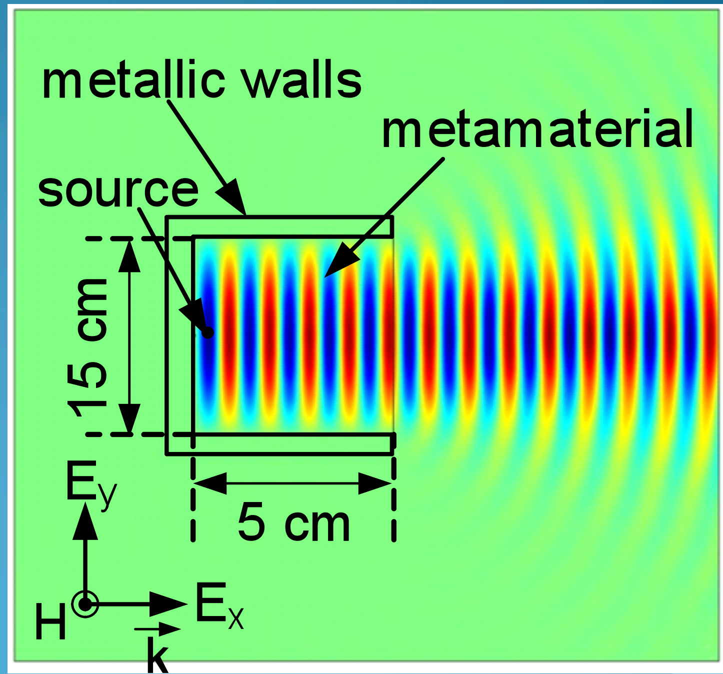
Calculated E field at 5, 10 and 40GHz.





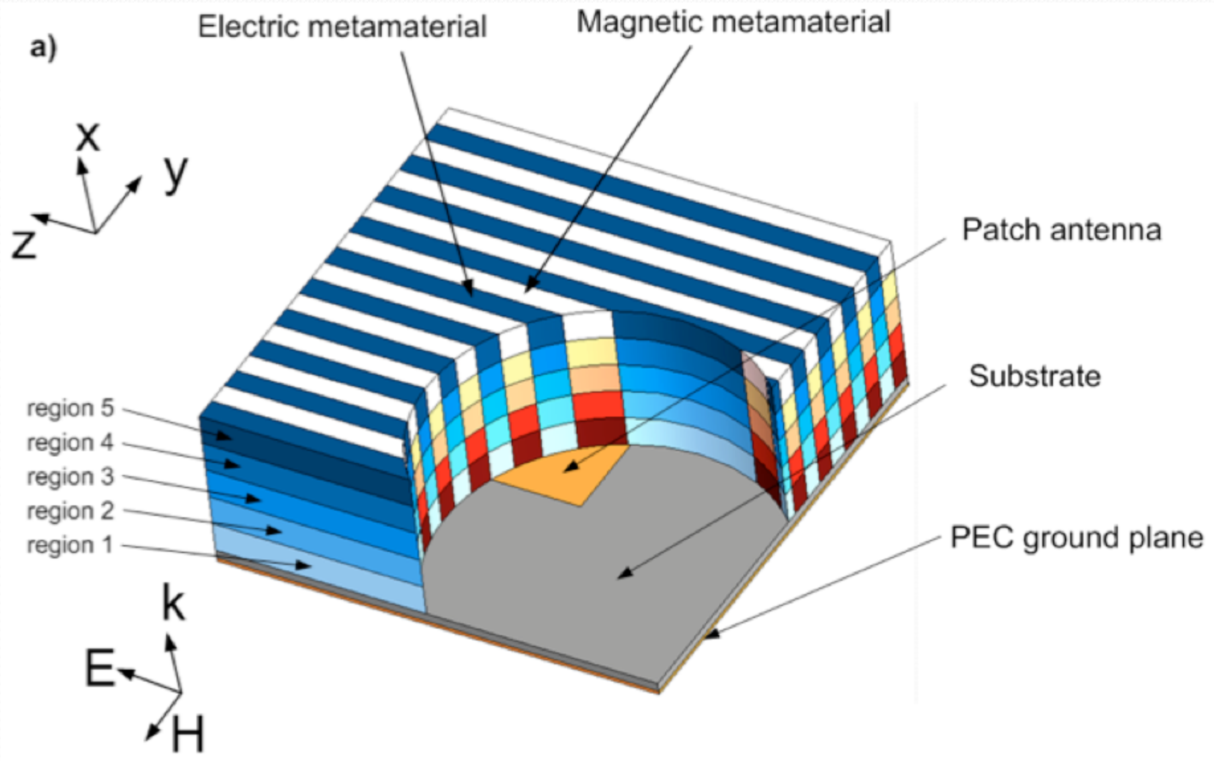
Discrétisation and Simulations.





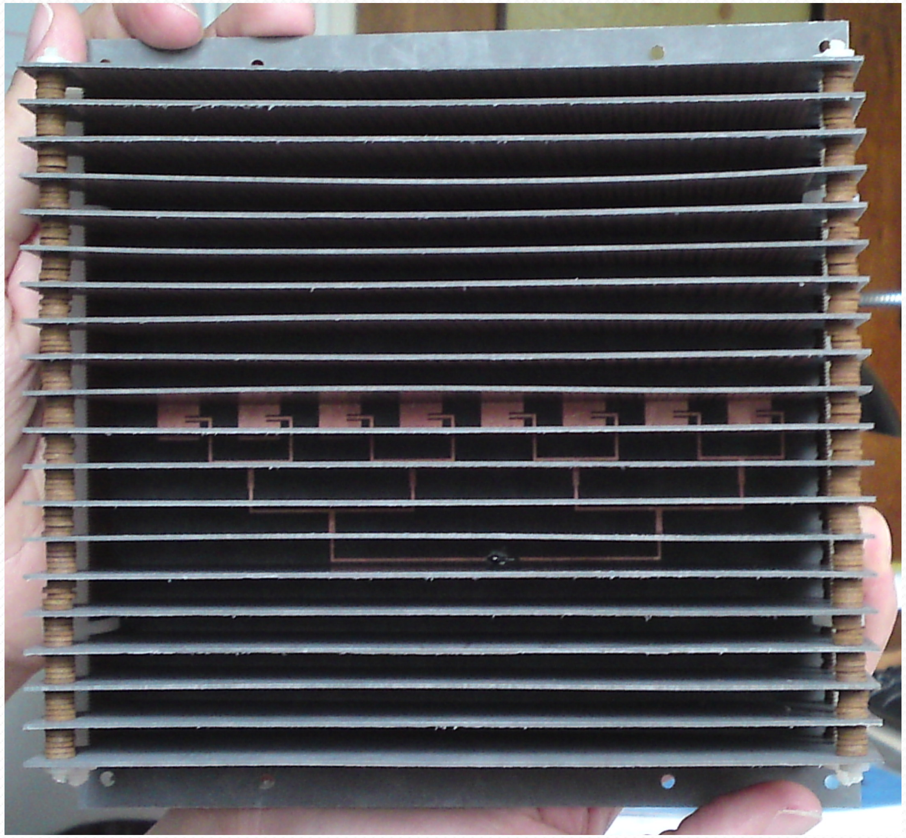
Ici on fait varier simultanément la permittivité et la perméabilité. (dans la cape seule la permittivité variait!)

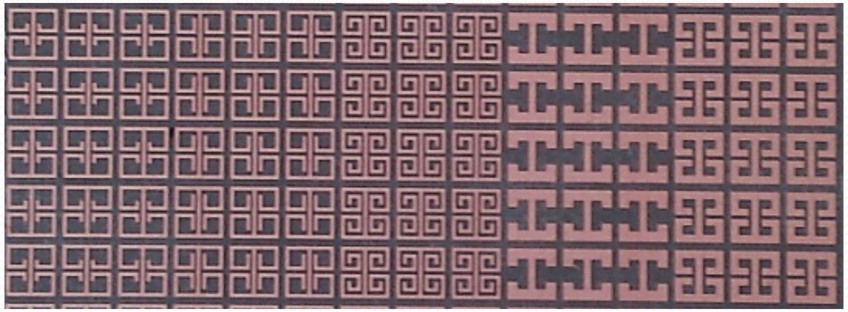
Realization: Schematic view.



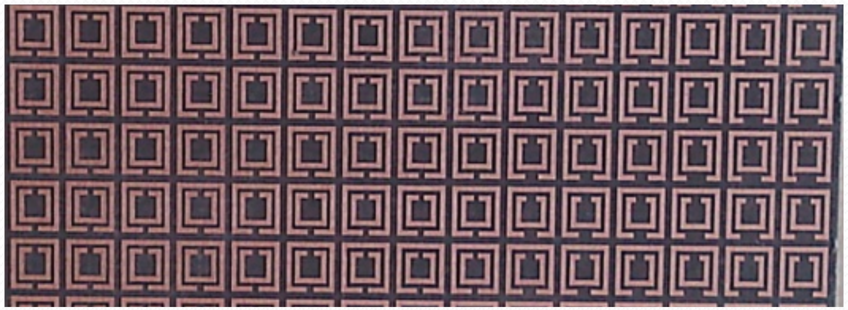
- The material is discretized in 5 regions.
- Electric and magnetic metamaterials are alternately stacked.

Realization.



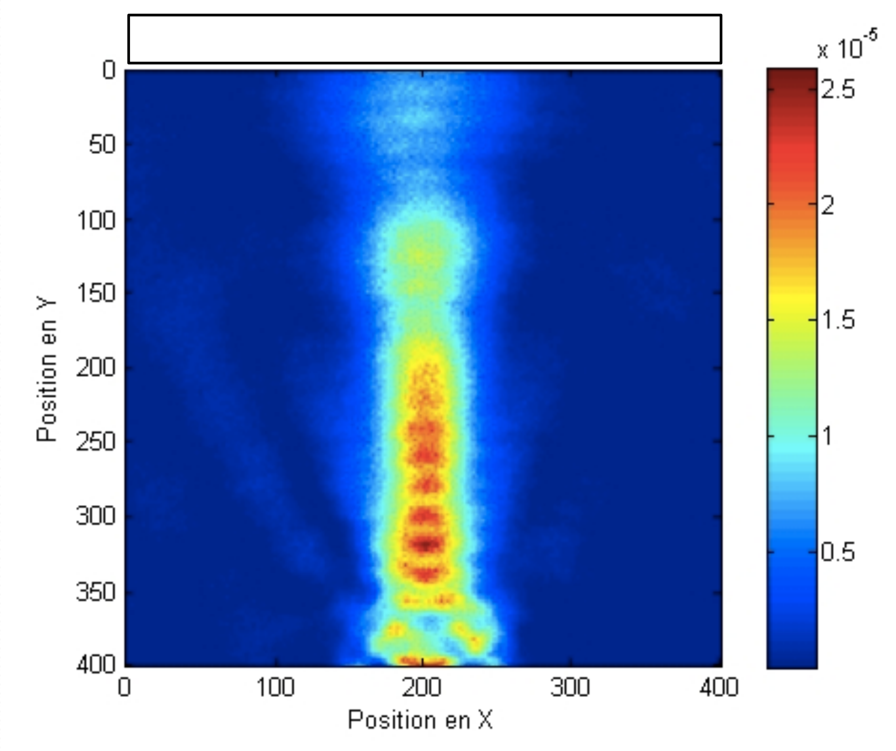


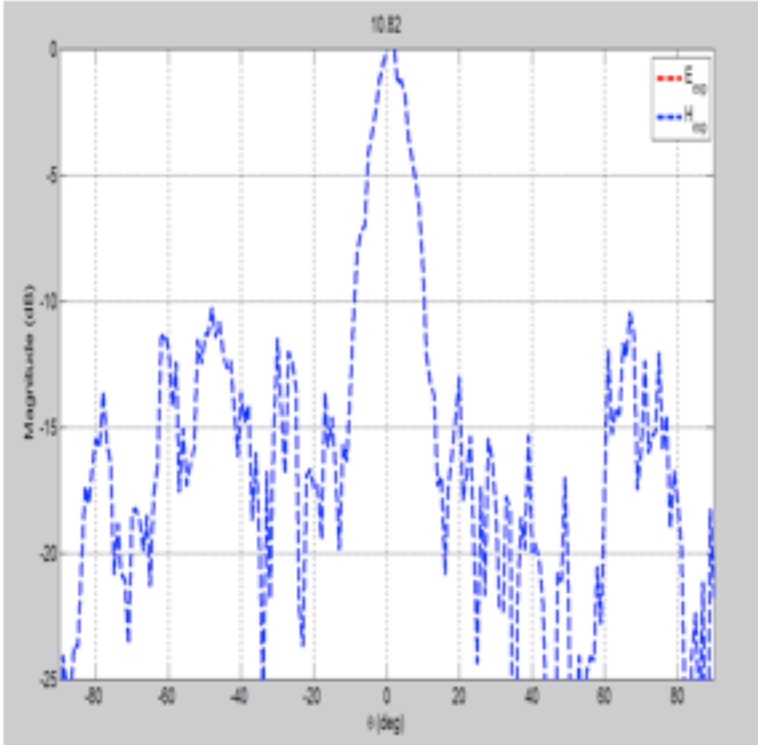
Electrical resonators



Magnetical resonators

Measurements.

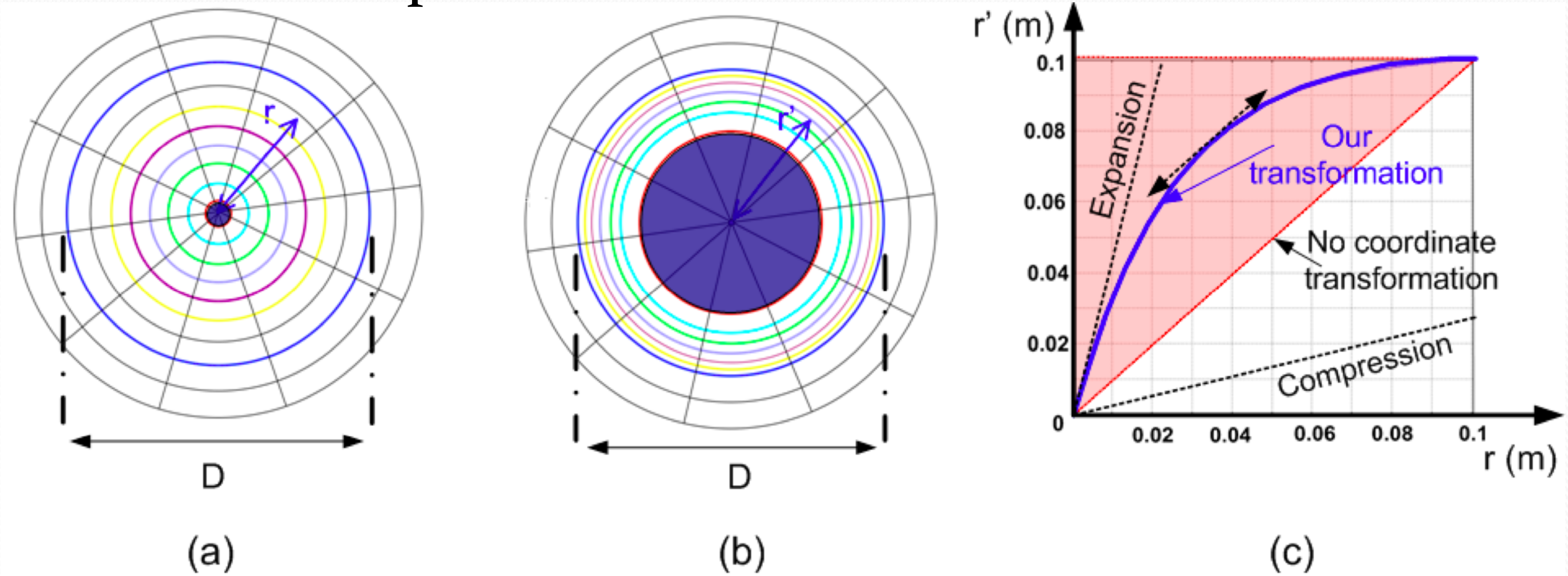




3ème exemple: modification de la taille apparente d'une structure rayonnante.

Principe de la transformation

- On veut transformer une source étendue directive en source isotrope.



- Expansion + compression de la région centrale autour de l'antenne.

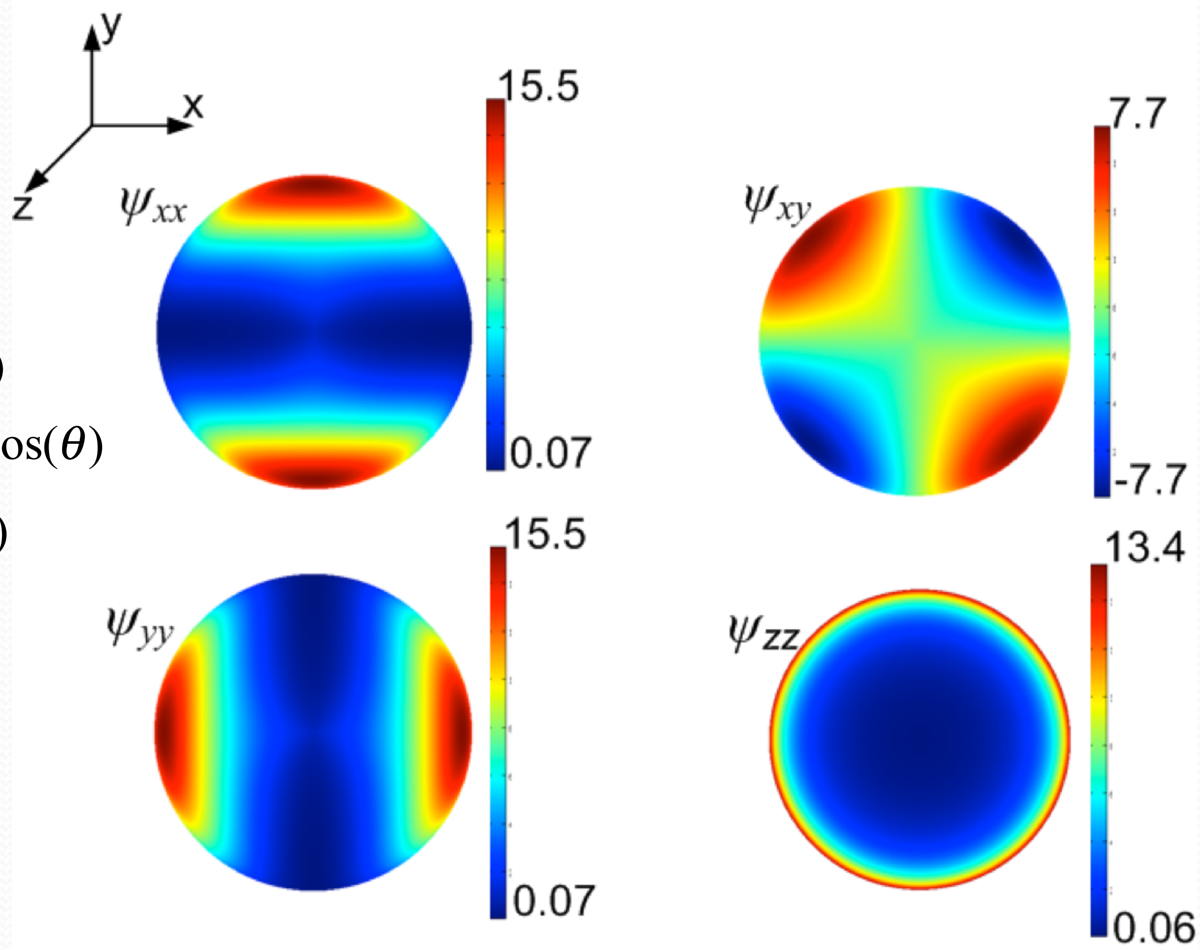
Principe: la transformation est de nouveau exponentielle.

$$\begin{cases} r' = \dfrac{D}{2}\dfrac{1-e^{qr}}{1-e^{\frac{qD}{2}}} \\ \theta' = \theta \\ z' = z \end{cases} = \begin{cases} r' = \alpha(1-e^{qr}) \\ \theta' = \theta \\ z' = z \end{cases} \quad \text{with} \quad \alpha = \frac{\mathrm{D}}{2}\frac{1}{1-\mathrm{e}^{\frac{\mathrm{qD}}{2}}}$$

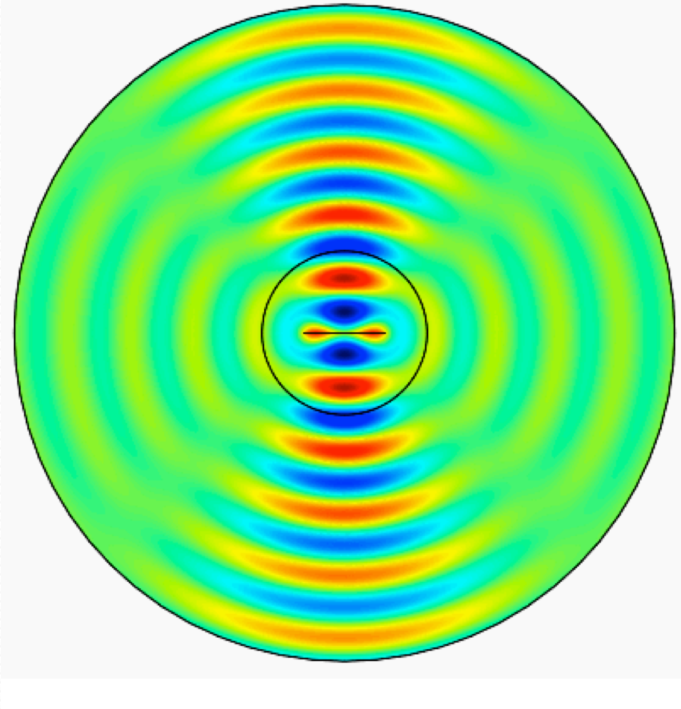
$$\overline{\overline{\psi}} = \begin{pmatrix} \psi_{rr} & 0 & 0 \\ 0 & \psi_{\theta\theta} & 0 \\ 0 & 0 & \psi_{zz} \end{pmatrix} = \begin{pmatrix} \dfrac{qr(r'-\alpha)}{r'} & 0 & 0 \\ 0 & \dfrac{r'}{qr(r'-\alpha)} & 0 \\ 0 & 0 & \dfrac{r}{r'q(r'-\alpha)} \end{pmatrix}$$

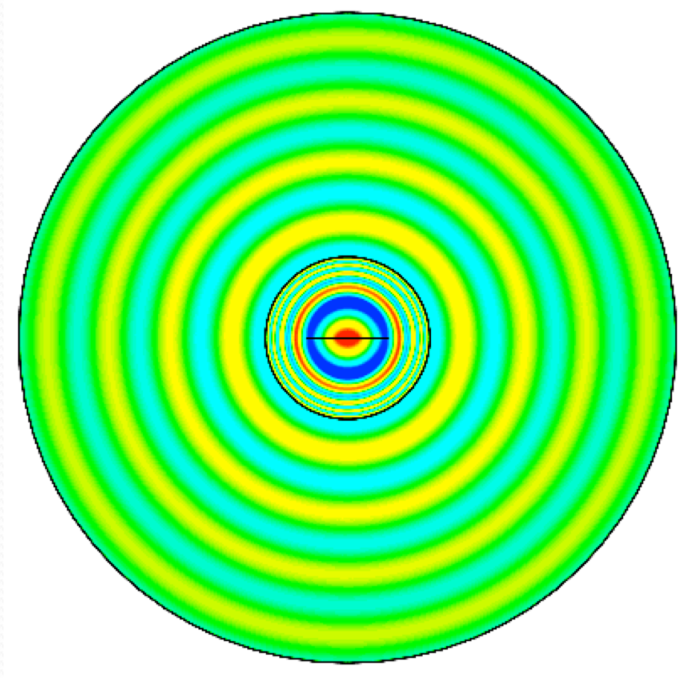
Paramètres électromagnétiques

$$\begin{cases} \psi_{xx} = \psi_{rr}\cos^2(\theta) + \psi_{\theta\theta}\sin^2(\theta) \\ \psi_{xy} = \psi_{yx} = (\psi_{rr} - \psi_{\theta\theta})\sin(\theta)\cos(\theta) \\ \psi_{yy} = \psi_{rr}\sin^2(\theta) + \psi_{\theta\theta}\cos^2(\theta) \end{cases}$$



Simulation





Antenne directive sans matériau

Antenne isotrope avec matériau

Conclusion: l'antenne a changé de taille apparente!

Conclusions

- La transformation d'espace permet de réaliser de nouveaux dispositifs micro-ondes.
- Elle nécessite l'utilisation de métamatériaux.
- Dans chaque cas la source est adaptée en impédance au matériau.
- Elle permet de modifier la taille apparente d'un objet.

Perspectives

- Challenges actuels:
  - Structures large bande?
  - Structures actives?
  - Transposition en optique?

- Perspectives: quelques exemples
  - Antennes miniatures?
  - Nouveaux composants optiques?
  - Invisibilité temporelle?
  - ....

Merci de votre attention!