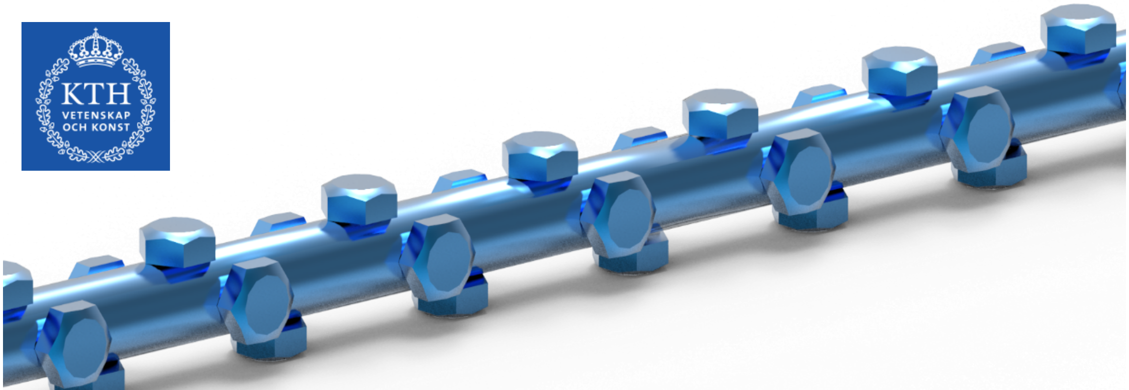


Higher symmetries for the design of periodic structures

Oscar Quevedo-Teruel

School of Electrical Engineering

KTH Royal Institute of Technology

Stockholm, Sweden.

1

Outline

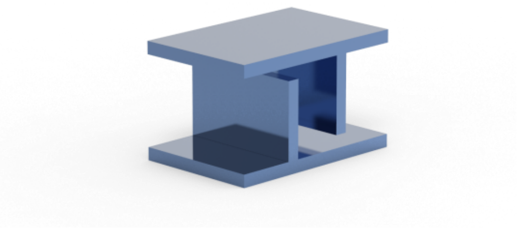
- Definition of higher symmetries:
  - Why should we study higher symmetries?
- Modelling of higher-symmetric structures:
  - Circuit models.
  - Mode matching.
- Applications of glide-symmetric structures:
  - EBG structures:
    - Gap waveguide technology.
    - Flanges.
  - Ultra wide band lenses.
  - CPW and leaky waves.
  - Microstrip technology and filters.
- Twist symmetries.
- Conclusions

2

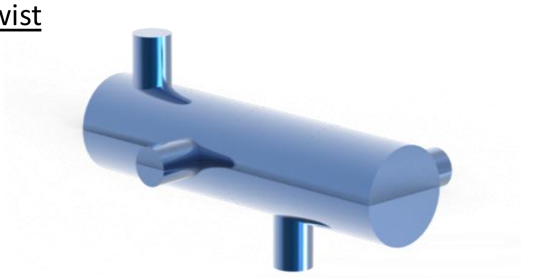
Definition of higher symmetries

- Definition: A UNIFORM periodically loaded guiding structure is said to possess a higher symmetry if the latter consists of more than a simple translation or reflection.

Glide



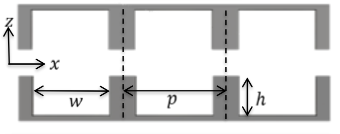
Twist



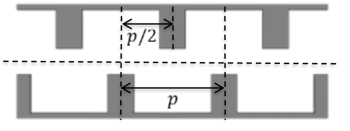
- A. Hessel, M. H. Chen, R. C. M. Li, and A. A. Oliner, "Propagation in periodically loaded waveguides with higher symmetries," *Proceedings of the IEEE*, vol. 61, no. 2, pp. 183–195, Feb. 1973.
- R. Mittra, S. Laxpati, "Propagation in a Wave Guide With Glide Reflection Symmetry", *Can. J. Phys.*, 43, 353-372 (1965)
- R. Kieburtz, J. Impagliazzo, "Multimode propagation on radiating traveling-wave structures with glide-symmetric excitation", *IEEE Trans. Antennas and Propag.*, 18, 3-7 (1970).
- P. J. Crepeau, P. R. McIsaac, "Consequences of Symmetry in Periodic Structures". *Proc. IEEE*, 52, 33-43 (1964).

Generalized Floquet Theorem

Conventional



Glide-symmetric



Floquet Theorem

$$\mathcal{T}_p[\mathbf{E}(x,y,z)] = \mathbf{E}(x+p,y,z) = e^{-jk_x p}\mathbf{E}(x,y,z)$$

$k_{\mathcal{T}}(\omega)p$ is peridic with period 2π

$$-\pi < k_{\mathcal{T}0}(\omega)p < \pi$$

Oliner's Generalized Floquet Theorem

$$\mathcal{G}_p[\mathbf{E}(x,y,z)] = \mathbf{E}(x+p/2,y,-z) = e^{-jk_x p/2}\mathbf{E}(x,y,z)$$

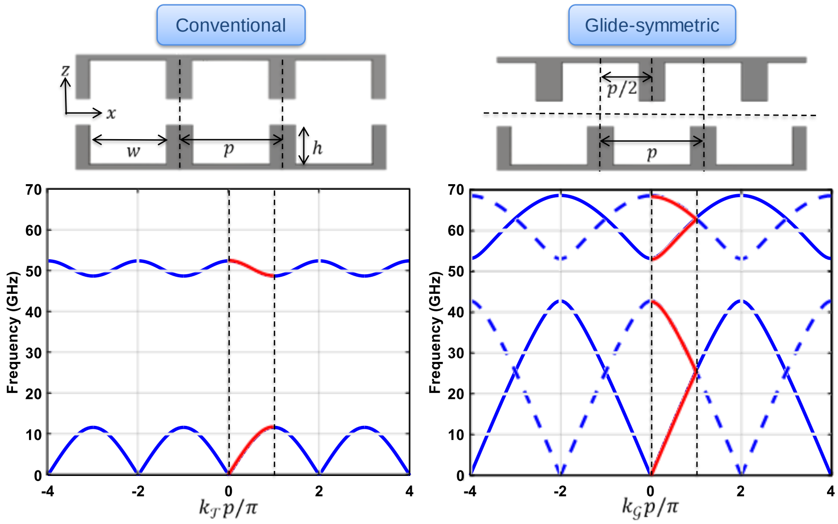
$k_{\mathcal{G}}(\omega)p$ is peridic with period 4π

$$-2\pi < k_{\mathcal{G}0}(\omega)p < 2\pi$$

$$k_{\mathcal{T}}(\omega)p = k_{\mathcal{G}}(\omega)p + 2\pi\nu \quad \nu = 0,1$$

- A. Hessel, M. H. Chen, R. C. M. Li, and A. A. Oliner, "Propagation in periodically loaded waveguides with higher symmetries," *Proceedings of the IEEE*, vol. 61, no. 2, pp. 183–195, Feb. 1973.

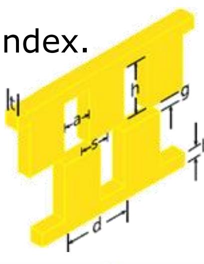
1D glide-symmetric structures

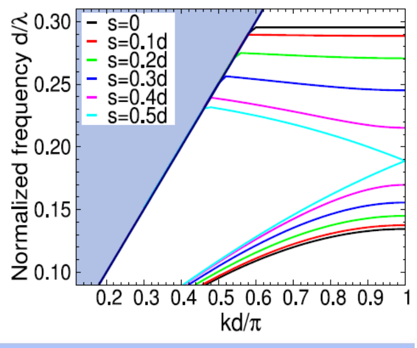


5

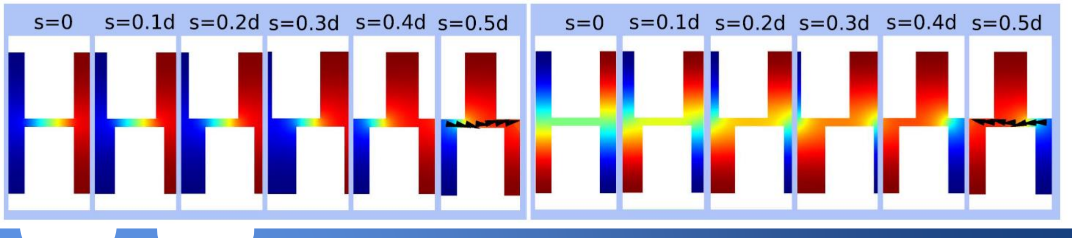
Operation 1: backward modes

- Glide symmetry was a phenomenon studied in physics:
  - Negative refractive index.





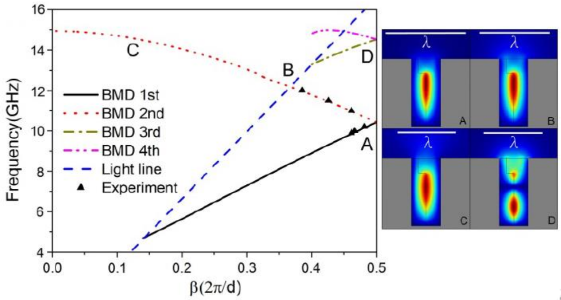
- R. Quesada, D. Martín-Cano, F. J. García-Vidal, J. Bravo-Abad, "Deep-subwavelength negative-index waveguiding enabled by coupled conformal surface plasmons", *Optics Letters*, vol. 39, no. 10, May 15, 2014.

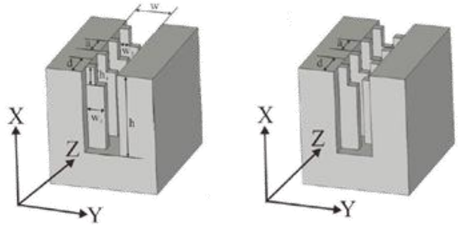


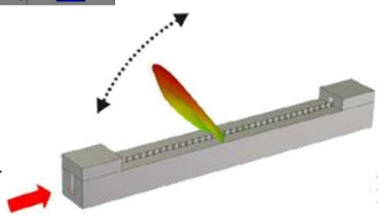
6

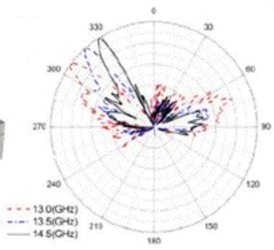
Operation 2: backward leaky waves

- Glide symmetry was studied for leaky wave antennas:
  - Backward radiation.









- J.-J. Wu, C.-J. Wu, D.-J. Hou, K. Liu, T.-J. Yang, "Propagation of Low-Frequency Spoof Surface Plasmon Polaritons in a Bilateral Cross-Metal Diaphragm Channel Waveguide in the Absence of Bandgap", *IEEE Photonics Journal*, vol 7, Jan 2015.

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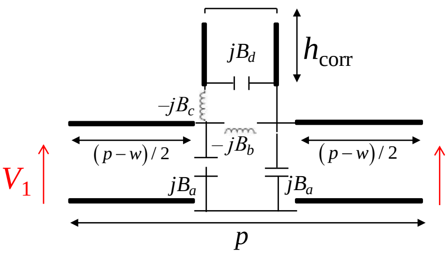
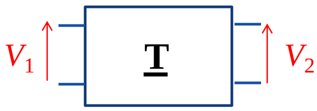
- Twist symmetries.
- Conclusions

Circuit model: Conventional structure

- It is possible to derive a longitudinal circuit that leads to a closed-form dispersion for a corrugated structure:

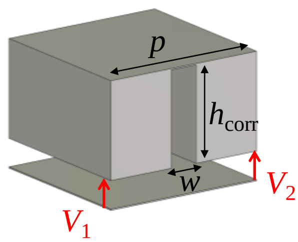


Equivalent circuit of a unit cell
(T junction between PPW)



$$\mathbf{T} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

$$\cos(\beta p) = A$$

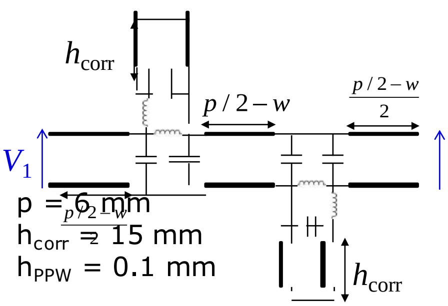


The parameters of the lumped elements are known *in closed form*!

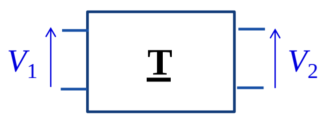
- N. Marcuvitz, Waveguide Handbook. Isha Books, 2013.

Circuit model: Glide symmetry

- It is possible to derive a longitudinal circuit that leads to a closed-form dispersion for the glide-symmetric structure:

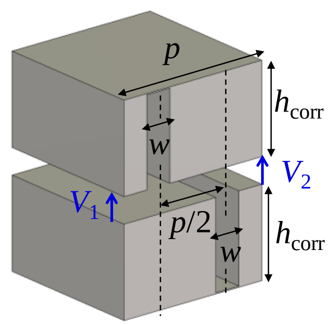


p = 6 mm
h_{corr} = 1.5 mm
h_{PPW} = 0.1 mm



$$\mathbf{T} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

$$\cos(\beta p) = \frac{A+D}{2}$$

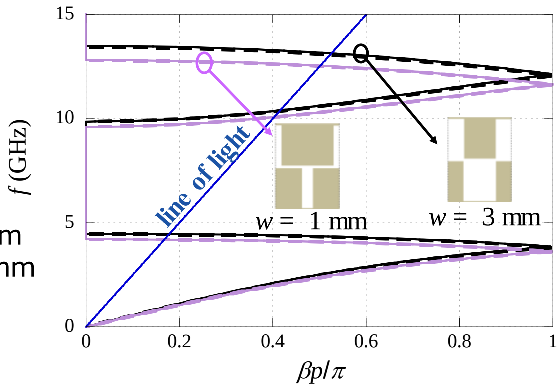


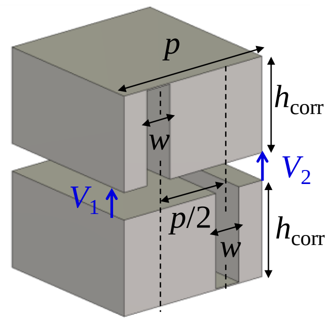
- G. Valerio, Z. Sipus, A. Grbic, O. Quevedo-Teruel, "Accurate Equivalent-Circuit Descriptions of Thin Glide-Symmetric Corrugated Metasurfaces", *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 5, pp. 2695-2700, May 2017.

Circuit model: Glide symmetry

- It is possible to derive a longitudinal circuit that leads to a closed-form dispersion for the glide-symmetric structure:

p = 6 mm
h_{corr} = 15 mm
h_{PPW} = 0.1 mm

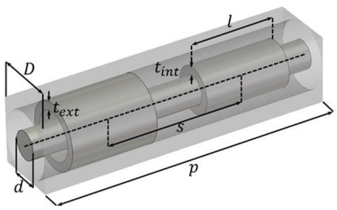


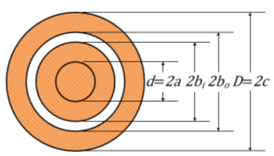


- G. Valerio, Z. Sipus, A. Grbic, O. Quevedo-Teruel, "Accurate Equivalent-Circuit Descriptions of Thin Glide-Symmetric Corrugated Metasurfaces", *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 5, pp. 2695-2700, May 2017.

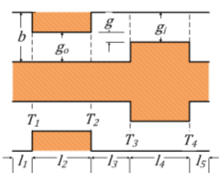
Circuit model: Polar glide symmetry

- A circuit is possible for coaxial lines: polar coordinates.





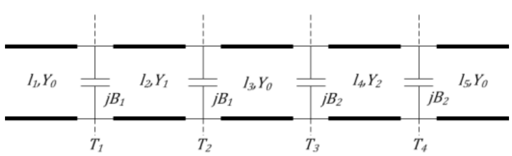
Cross-section view



Side view

$$\frac{Y_1}{Y_0} = \frac{\ln \frac{c}{a}}{\ln \frac{b_o}{a}},$$

$$\frac{B_1}{Y_0} = \frac{2bA_1}{\lambda}\left[2\ln\left(\frac{1-\alpha^2}{4\alpha}\right)\left(\frac{1+\alpha}{1-\alpha}\right)^{(\alpha+\frac{1}{\alpha})/2} + \frac{1}{2}\left(\frac{b}{\lambda}\right)^2\left(\frac{1-\alpha}{1+\alpha}\right)^{4\alpha}\left(\frac{5\alpha^2-1}{1-\alpha^2}+\frac{4}{3}\frac{\alpha^2 C}{A}\right)^2 + 4\frac{A+A'+2C}{AA'-C^2}+\frac{A_2}{2}\right],$$

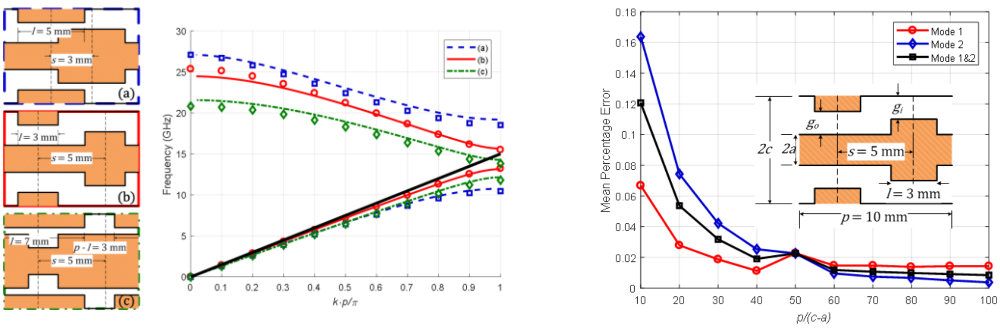


Equivalent circuit

- Q. Chen, F. Ghasemifard, G. Valerio, O. Quevedo-Teruel, "Modeling and Dispersion Analysis of Coaxial Lines with Higher Symmetries" *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 10, pp. 4338-4345, Oct. 2018.

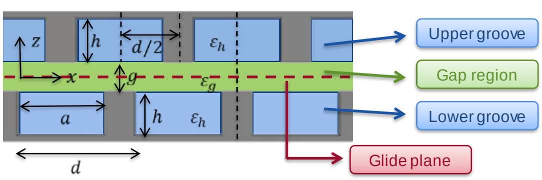
Circuit model: Polar glide symmetry

- Results:
  - Good agreement with commercial software.
  - The models are limited to low coupling between sub-elements.



• Q. Chen, F. Ghasemifard, G. Valerio, O. Quevedo-Teruel, “Modeling and Dispersion Analysis of Coaxial Lines with Higher Symmetries” *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 10, pp. 4338-4345, Oct. 2018.

Mode-matching: 1D glide symmetry



TE$_y$-modes ($H_y \neq 0$ and $E_y = 0$) are the first dominant modes that can propagate in the structure.

E_x and H_y need to be matched.

In the gap region:

$$E_x^{\mathrm{Gap}}(x,z) = \frac{1}{d}\sum_p e^{-jk_{x,p}x}\left[A_p \sin(k_{z,p}z) + B_p \cos(k_{z,p}z)\right]$$

$$k_{x,p} = k_{x,0} + 2\pi p/d \quad \text{and} \quad k_{z,p} = \sqrt{\varepsilon_g k_0^2 - k_{x,p}^2 - k_y^2}$$

In the lower groove region:

$$E_x^{\mathrm{low}}(x,-g/2) = \sum_m [1 - R_m] C_m \,\Phi_m(x)$$

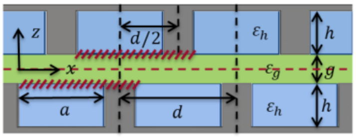
$$R_m = e^{-j2q_m h} \quad \text{and} \quad q_m = \sqrt{\varepsilon_h k_0^2 - (m\pi/a)^2 - k_y^2}$$

In the upper groove region (generalized Floquet theorem):

$$E_x^{\mathrm{up}}\left(x,\frac{g}{2}\right) = e^{-jk_{x,0}d/2} E_x^{\mathrm{low}}\left(x-\frac{d}{2},-\frac{g}{2}\right)$$

• F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, "Dispersion Analysis of 2-D Glide-Symmetric Corrugated Metasurfaces Using Mode-Matching Technique," *IEEE Microwave and Wireless Components Letters*, vol. 28, no. 1, pp. 1-3, Jan. 2018.

Mode-matching: 1D glide symmetry



Imposing BC for E_x $(0 < x < d)$

$$\begin{cases} -A_p \sin(k_{z,p}g/2) + B_p \cos(k_{z,p}g/2) = \tilde{E}_x^{\text{low}}(k_{x,p}, -g/2) \\ +A_p \sin(k_{z,p}g/2) + B_p \cos(k_{z,p}g/2) = (-1)^p \tilde{E}_x^{\text{low}}(k_{x,p}, -g/2) \end{cases}$$

$$E_x^{\text{Gap}}(x,z) = \frac{1}{d}\sum_p e^{-jk_{x,p}x}\left[A_p \sin(k_{z,p}z) + B_p \cos(k_{z,p}z)\right]$$

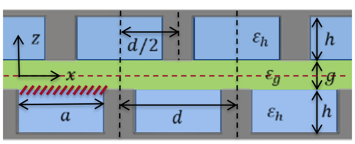
$$\tilde{E}_x^{\text{low}}(k_{x,p}, -g/2) = \sum_m [1 - R_m] C_m \tilde{\Phi}_m(k_{x,p})$$

p is odd $\Rightarrow \begin{cases} A_p = -\dfrac{\tilde{E}_x^{\text{low}}(k_{x,p}, -g/2)}{\sin(k_{z,p}g/2)} \\ B_p = 0 \end{cases} \Rightarrow \mathbf{E}_t^{\text{Gap}}$ is odd $\Rightarrow$ Glide plane is equivalent to a PEC

p is even $\Rightarrow \begin{cases} A_p = 0 \\ B_p = +\dfrac{\tilde{E}_x^{\text{low}}(k_{x,p}, -g/2)}{\cos(k_{z,p}g/2)} \end{cases} \Rightarrow \mathbf{E}_t^{\text{Gap}}$ is even $\Rightarrow$ Glide plane is equivalent to a PMC

- F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, "Dispersion Analysis of 2-D Glide-Symmetric Corrugated Metasurfaces Using Mode-Matching Technique," *IEEE Microwave and Wireless Components Letters*, vol. 28, no. 1, pp. 1-3, Jan. 2018.

Mode-matching: 1D glide symmetry



Imposing BC for H_y $(0 < x < a)$

$$\Rightarrow \sum_m \alpha_{n,m} C_m = 0$$

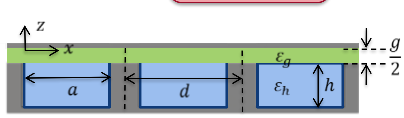
$$\alpha_{n,m} = \sum_p \tilde{f}_p(k_{z,p}) \frac{\beta_{n,m}(k_{x,p})}{k_{z,p}} - \delta_{n,m}\frac{jd}{q_m}\left(\frac{1+R_m}{1-R_m}\right)\left(\frac{\varepsilon_h k_0^2 - k_y^2}{\varepsilon_g k_0^2 - k_y^2}\right)$$

$$\beta_{n,m}(k_{x,p}) = \tilde{\Phi}_m(k_{x,p})\tilde{\Phi}_{m'}(-k_{x,p})$$

Glide $\rightarrow$ $\tilde{f}_p(k_{z,p}) = \begin{cases} +\cot(k_{z,p}g/2) & \text{if } p \text{ is odd} \\ -\tan(k_{z,p}g/2) & \text{if } p \text{ is even} \end{cases}$

Vertical Spectral Function

Non-glide $\rightarrow$ $\tilde{f}_p(k_{z,p}) = \cot(k_{z,p}g/2)$



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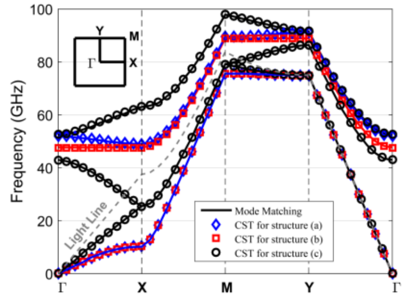
1D Mode-matching

- Results:



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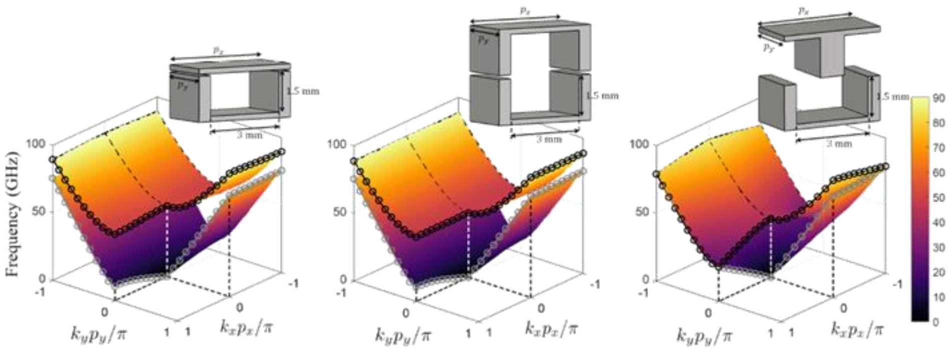
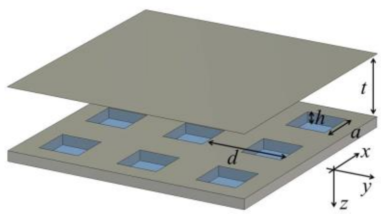


17

Mode-matching: 2D Formulation

- It is possible to model these structures with fast mode-matching codes:



$$\left|\mathbf{E}_t\big|_{z=0^-}\right\rangle = \frac{1}{d^2}\sum_{pq}\sin\left(k_{z,pq}h_{\mathrm{PPW}}\right)\begin{pmatrix}A^x_{pq}\\ A^y_{pq}\end{pmatrix}\left|e^{i\left(k_{x,p}x+k_{y,q}y\right)}\right\rangle$$

$$\left|\mathbf{E}_t\big|_{z=0^+}\right\rangle = \sum_{(m,n)} r^-_{mn}C^h_{mn}\left|\mathbf{\Phi}^h_{mn}(x,y)\right\rangle + r^-_{mn}C^e_{mn}\left|\mathbf{\Phi}^e_{mn}(x,y)\right\rangle \qquad 0\le x,y\le a$$

$$\left|\eta_0\,\mathbf{H}_t\big|_{z=0^+}\right\rangle = \sum_{(m,n)} C^h_{mn}r^+_{mn}\frac{q_{mn}}{k_0}\left|\hat{\mathbf{z}}\times\mathbf{\Phi}^h_{mn}(x,y)\right\rangle + C^e_{mn}r^+_{mn}\frac{k_0\varepsilon_r}{q_{mn}}\left|\hat{\mathbf{z}}\times\mathbf{\Phi}^e_{mn}(x,y)\right\rangle \qquad 0\le x,y\le a$$

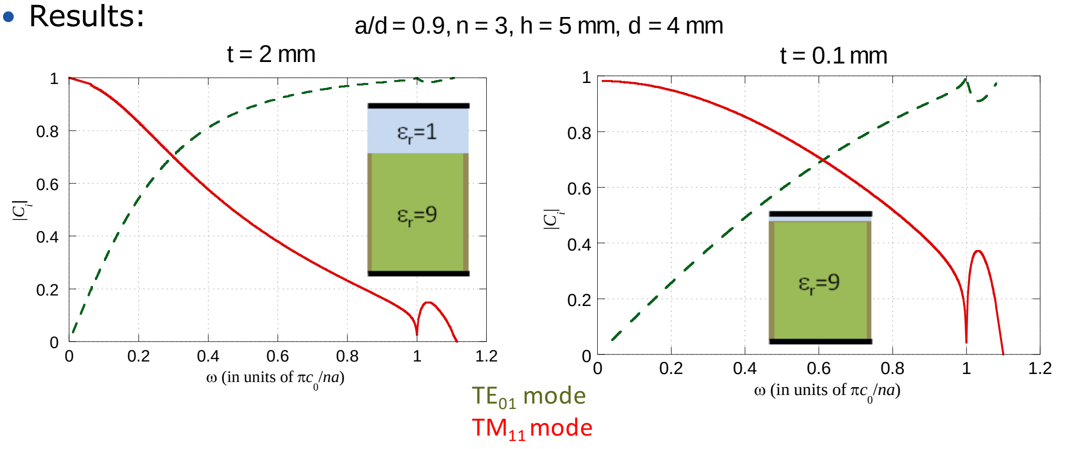
$$\left|\mathbf{\Phi}^h_{mn}(x,y)\right\rangle = \left|\hat{\mathbf{x}}n\varphi^x_{mn}(x,y)-\hat{\mathbf{y}}m\varphi^y_{mn}(x,y)\right\rangle,\quad \left|\mathbf{\Phi}^e_{mn}(x,y)\right\rangle = \left|\hat{\mathbf{x}}m\varphi^x_{mn}(x,y)+\hat{\mathbf{y}}n\varphi^y_{mn}(x,y)\right\rangle \qquad \varphi^x_{mn}(x,y)=\begin{cases}\frac{2}{a}\cos\left(\frac{m\pi x}{a}\right)\sin\left(\frac{n\pi y}{a}\right) & m\neq 0\\ \frac{1}{a}\sqrt{\frac{2}{a}}\sin\left(\frac{n\pi y}{a}\right) & m=0\end{cases}$$

- F.-J. Garcia-Vidal, L. Martín-Moreno, J.-B. Pendry, “Surfaces with holes in them: new plasmonic metamaterials” *J. Opt. A: Pure Appl. Opt.* 7 S97, 2005.
- G. Valerio, Z. Sipus, A. Grbic, O. Quevedo-Teruel, “The Role of Resonances in Plasmonic Holey Metasurfaces for the Design of Artificial Flat Lenses,” *Optics Letters,* vol. 42, no. 10, pp. 2026-2029, 2017.

18

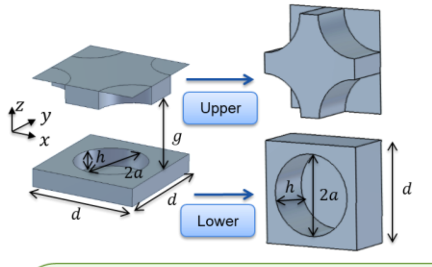
Mode-matching: Modes importance

- Results:



- F.-J. Garcia-Vidal, L. Martín-Moreno, J.-B. Pendry, "Surfaces with holes in them: new plasmonic metamaterials" *J. Opt. A: Pure Appl. Opt.* 7 S97, 2005.
- G. Valerio, Z. Sipus, A. Grbic, O. Quevedo-Teruel, "The Role of Resonances in Plasmonic Holey Metasurfaces for the Design of Artificial Flat Lenses," *Optics Letters,* vol. 42, no. 10, pp. 2026-2029, 2017.

Mode-matching: 2D glide symmetry



In the hole region:

$$\mathbf{E}_t^{\text{Hole}}(\boldsymbol{\rho}, z=-g/2) = \sum_m [1 - R_m] C_m \, \boldsymbol{\Phi}_m(\boldsymbol{\rho})$$

$$\mathbf{H}_t^{\text{Hole}}(\boldsymbol{\rho}, z=-g/2) = \sum_m [1 + R_m] Y_m C_m [\hat{z} \times \boldsymbol{\Phi}_m(\boldsymbol{\rho})]$$

$$R_m = e^{-j2k_{zm}h} \quad \text{and} \quad k_{zm} = \sqrt{k_0^2 - k_t^2}$$

In the gap region:

$$\mathbf{E}_t^{\text{Gap}} = \frac{1}{d^2} \sum_{p,q} e^{-j(k_{x,p}x + k_{y,q}y)} \left[\begin{pmatrix} A_{pq}^x \\ A_{pq}^y \end{pmatrix} \sin(k_{z,pq}z) + \begin{pmatrix} B_{pq}^x \\ B_{pq}^y \end{pmatrix} \cos(k_{z,pq}z) \right]$$

$$\mathbf{H}_t^{\text{Gap}} = \frac{1}{d^2} \sum_{p,q} e^{-j(k_{x,p}x + k_{y,q}y)} \left[\begin{pmatrix} D_{pq}^x \\ D_{pq}^y \end{pmatrix} \sin(k_{z,pq}z) + \begin{pmatrix} F_{pq}^x \\ F_{pq}^y \end{pmatrix} \cos(k_{z,pq}z) \right]$$

$$k_{x,p} = k_{x,0} + \frac{2\pi p}{d}$$

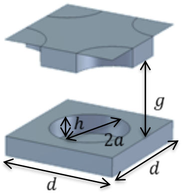
$$k_{y,q} = k_{y,0} + \frac{2\pi q}{d}$$

$$k_{z,p} = \sqrt{k_0^2 - k_{x,p}^2 - k_{y,q}^2}$$

- F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, G. Valerio, "Analyzing Glide-Symmetric Holey Metasurfaces Using a Generalized Floquet Theorem", *IEEE Access*, vol. 6, pp. 71743-71750, 2018.

Mode-matching: 2D glide symmetry

Imposing BC for $\mathbf{E}_t$



$$\mathbf{E}_t^{\mathrm{Gap}}\left(x,y,z=-\frac{g}{2}\right)=\mathbf{E}_t^{\mathrm{Hole}}\left(\boldsymbol{\rho},z=-\frac{g}{2}\right)=\sum_m[1-R_m]C_m\,\boldsymbol{\Phi}_m(\boldsymbol{\rho})$$

$$\mathbf{E}_t^{\mathrm{Gap}}\left(x+\frac{d}{2},y+\frac{d}{2},z=\frac{g}{2}\right)=e^{-\mathrm{j}k_{x,0}\frac{d}{2}}e^{-\mathrm{j}k_{y,0}\frac{d}{2}}\mathbf{E}_t^{\mathrm{Hole}}\left(\boldsymbol{\rho},z=-\frac{g}{2}\right)$$

$$\mathbf{E}_t^{\mathrm{Gap}}=\frac{1}{d^2}\sum_{p,q}e^{-\mathrm{j}(k_{x,p}x+k_{y,q}y)}\left[\begin{pmatrix}A_{pq}^x\\A_{pq}^y\end{pmatrix}\sin(k_{z,pq}z)+\begin{pmatrix}B_{pq}^x\\B_{pq}^y\end{pmatrix}\cos(k_{z,pq}z)\right]$$

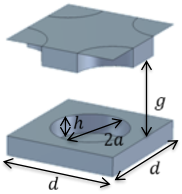
If $p+q$ is odd $\Rightarrow \begin{cases}\begin{pmatrix}A_{pq}^x\\A_{pq}^y\end{pmatrix}=-\dfrac{\tilde{\mathbf{E}}_t^{\mathrm{WG}}(k_{x,p},k_{y,q})}{\sin(k_{z,pq}g/2)}\\ \begin{pmatrix}B_{pq}^x\\B_{pq}^y\end{pmatrix}=\mathbf{0}\end{cases}$ $\Rightarrow \mathbf{E}_t^{\mathrm{Gap}}$ is odd $\Rightarrow$ Glide plane is equivalent to a PEC

If $p+q$ is even $\Rightarrow \begin{cases}\begin{pmatrix}A_{pq}^x\\A_{pq}^y\end{pmatrix}=\mathbf{0}\\ \begin{pmatrix}B_{pq}^x\\B_{pq}^y\end{pmatrix}=\dfrac{\tilde{\mathbf{E}}_t^{\mathrm{WG}}(k_{x,p},k_{y,q})}{\cos(k_{z,pq}g/2)}\end{cases}$ $\Rightarrow \mathbf{E}_t^{\mathrm{Gap}}$ is even $\Rightarrow$ Glide plane is equivalent to a PMC

- F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, G. Valerio, "Analyzing Glide-Symmetric Holey Metasurfaces Using a Generalized Floquet Theorem", *IEEE Access*, vol. 6, pp. 71743-71750, 2018.

Mode-matching: 2D glide symmetry

Imposing BC for $\mathbf{H}_t$ and projecting it on $\boldsymbol{\Phi}_n(\boldsymbol{\rho})$ over the hole aperture:



$$\sum_m \alpha_{nm}\,C_m=0$$

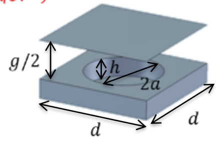
$$\alpha_{n,m}=\sum_p \tilde{f}_{pq}(k_{z,pq})\frac{\beta_{n,m}(k_{x,p},k_{y,q})}{k_{z,pq}}+\mathrm{j}k_0\eta_0 d^2\frac{1+R_m}{1-R_m}Y_m I_{nm}$$

Glide → $\tilde{f}_{pq}(k_{z,pq})$ $-\int$ $+\cot(k_{z,pq}g/2)$ if $p+q$ is odd

Non-glide → $\tilde{f}_{pq}(k_{z,pq})=\cot(k_{z,pq}g/2)$

$$\beta_{n,m}(k_{x,p},k_{y,q})\propto\tilde{\boldsymbol{\Phi}}_m(k_{x,p},k_{y,q}),\tilde{\boldsymbol{\Phi}}_n(-k_{x,p},-k_{y,q})$$

$$\tilde{\boldsymbol{\Phi}}_m(k_{x,p},k_{y,q})=\int_{S_{hole}}\boldsymbol{\Phi}_m(\boldsymbol{\rho})\,e^{\mathrm{j}(k_{x,p}x+k_{y,q}y)}\,ds$$



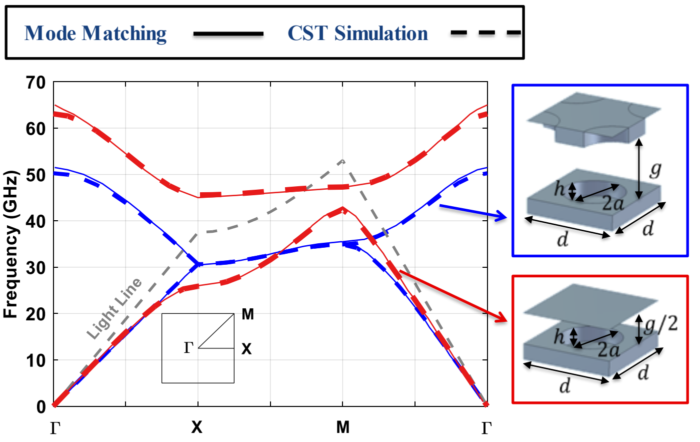
- F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, G. Valerio, "Analyzing Glide-Symmetric Holey Metasurfaces Using a Generalized Floquet Theorem", *IEEE Access*, vol. 6, pp. 71743-71750, 2018.

Mode-matching: 2D glide symmetry

Glide
8 waveguide modes
25 Floquet modes

Non-glide
11 waveguide modes
49 Floquet modes

$d = 4$ mm
$a = 1.6$ mm
$h = 1.5$ mm
$g = 0.2$ mm

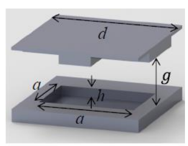


- F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, G. Valerio, "Analyzing Glide-Symmetric Holey Metasurfaces Using a Generalized Floquet Theorem", *IEEE Access*, vol. 6, pp. 71743-71750, 2018.

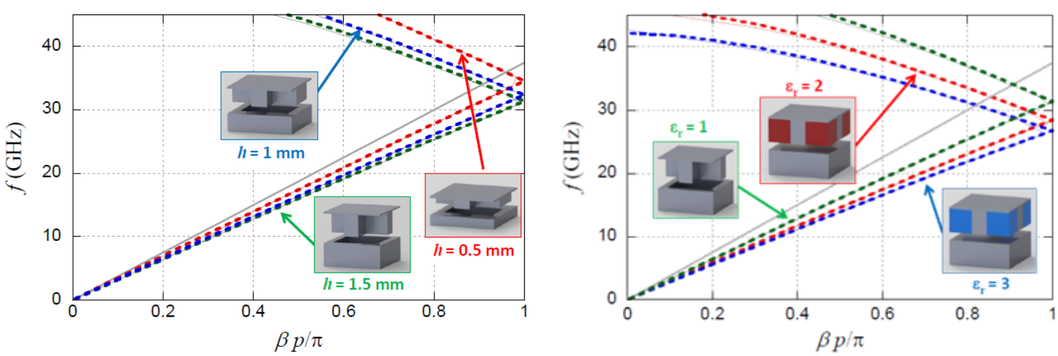
Mode-matching: 2D glide symmetry

- Results for squared holes:

——— mode matching
-------- CST



d = 1.5 mm
g = 0.5 mm
h = 4 mm
a = b = 3 mm

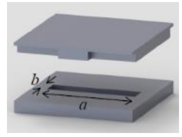


- G. Valerio, F. Ghasemifard, Z. Sipus, O. Quevedo-Teruel, "Glide-Symmetric All-Metal Holey Metasurfaces for Low-Dispersive Artificial Materials: Modeling and Properties," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 7, pp. 3210-3223, July 2018.

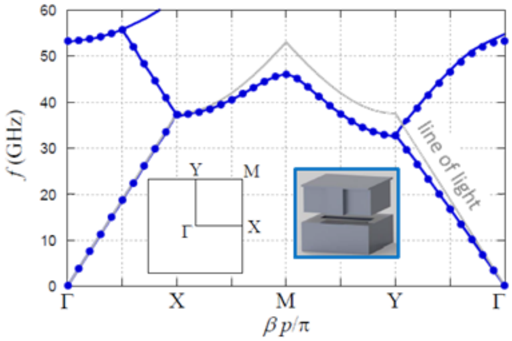
Mode-matching: Anisotropy

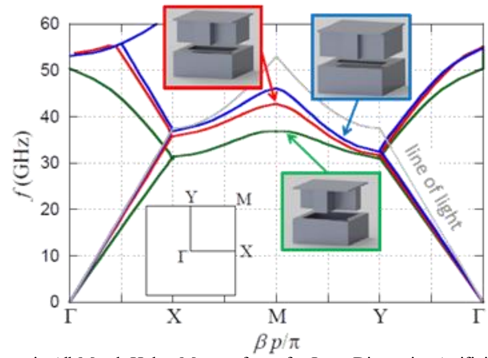
- Results for rectangular holes:

——— mode matching
-------- CST



d = 1.5 mm
g = 0.5 mm
h = 4 mm
b = a/2 = 1.5



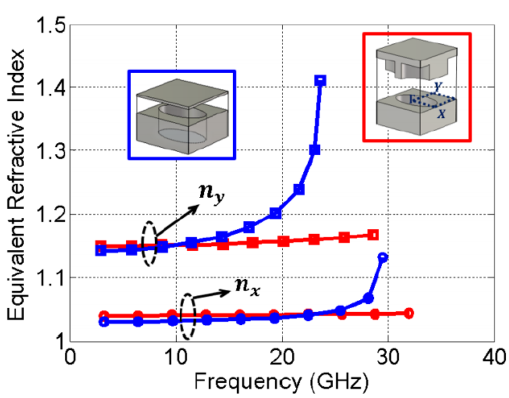


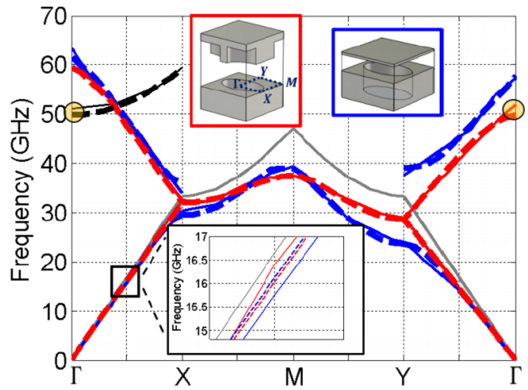
- G. Valerio, F. Ghasemifard, Z. Sipus, O. Quevedo-Teruel, "Glide-Symmetric All-Metal Holey Metasurfaces for Low-Dispersive Artificial Materials: Modeling and Properties," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 7, pp. 3210-3223, July 2018.

Mode-matching: Anisotropy

- Results for elliptical holes:

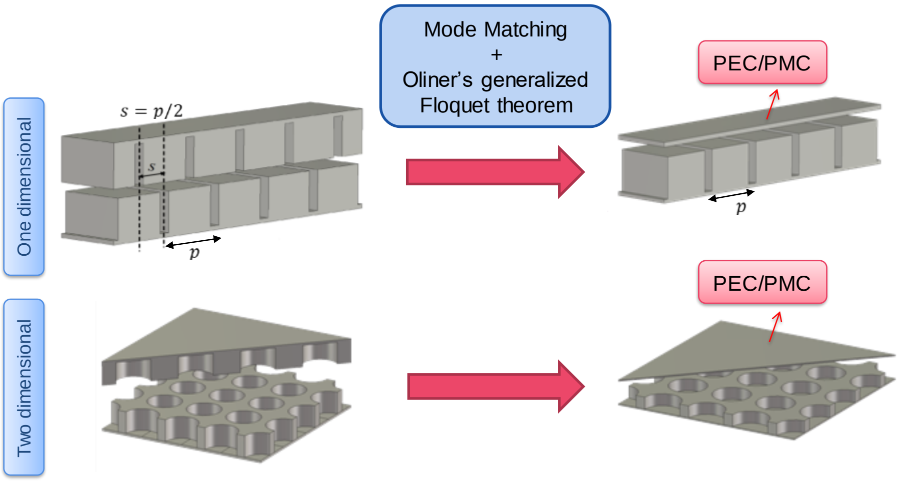
——— mode matching
-------- CST





- A. Alex-Amor, F. Ghasemifard, G. Valerio, P. Padilla, J. M. Fernandez-Gonzalez, O. Quevedo-Teruel, "Glide-Symmetric Metallic Structures with Elliptical Holes", *submitted to IEEE Transactions on Microwave Theory and Techniques.*

Spatial combination of PEC/PMC



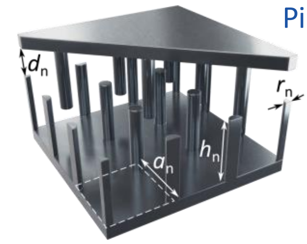
Outline

- Definition of higher symmetries:
  - Why should we study higher symmetries?
- Modelling of higher-symmetric structures:
  - Circuit models.
  - Mode matching.
- Applications of glide-symmetric structures:
  - EBG structures:
    - Gap waveguide technology.
    - Flanges.
  - Ultra wide band lenses.
  - CPW and leaky waves.
  - Microstrip technology and filters.
- Twist symmetries.
- Conclusions

2D Glide-symmetric configurations

- Configurations:
  - Metallic inclusions: Bed of nails.
  - Holey structures.
- Four groups under study:
  - Fully-metallic EBG:
    - Low cost gap waveguide technology.
    - Low cost flanges.
  - Planar lenses:
    - Ultra wideband lens antennas with steerable angle.
  - Slotted lines:
    - Low-dispersive and tuneable low-propagation.
    - Control of stop-bands.
  - Microstrip technology:
    - Increased bandwidth or attenuation in filters.

Pins

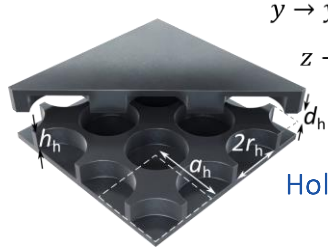


2D:

$x \to x + a/2$

$y \to y + a/2$

$z \to -z$



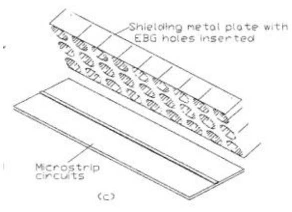
Holes

Outline

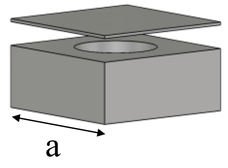
- Definition of higher symmetries:
  - Why should we study higher symmetries?
- Modelling of higher-symmetric structures:
  - Circuit models.
  - Mode matching.
- Applications of glide-symmetric structures:
  - EBG structures:
    - Gap waveguide technology.
    - Flanges.
  - Ultra wide band lenses.
  - CPW and leaky waves.
  - Microstrip technology and filters.
- Twist symmetries.
- Conclusions

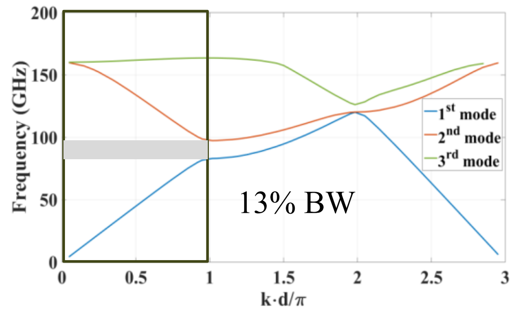
Previous works on holey EBG:

- Holey Band gap structure was introduced for packaging microstrip circuits.
- This structure has a very narrow stopband or stop band in only one single direction.



a= 1.62 mm
Radius of holes = 0.6 mm
Depth of holes = 1.2 mm
Gap = 0.05 mm

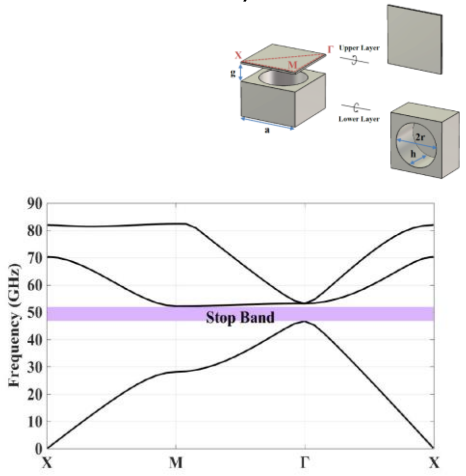


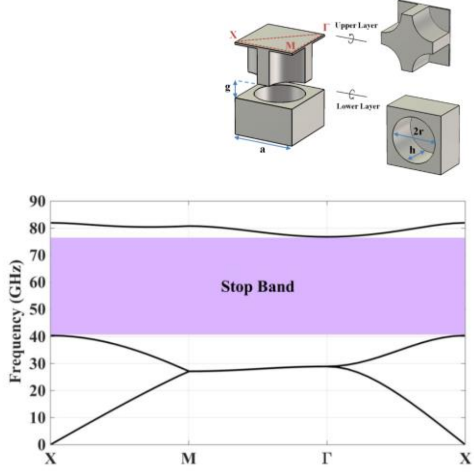


- Dawn, Debasis, Yoji Ohashi, and Toshihiro Shimura. "A novel electromagnetic bandgap metal plate for parallel plate mode suppression in shielded structures." *IEEE Microwave and Wireless Components Letters*, vol. 12, pp. 166-168, 2002.

EBG: Motivation

- Conventional holey structure versus glide symmetry:

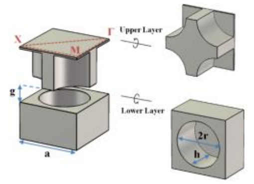


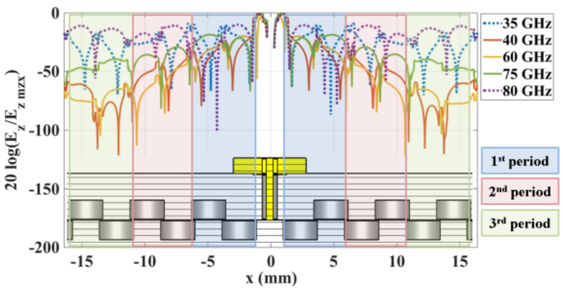


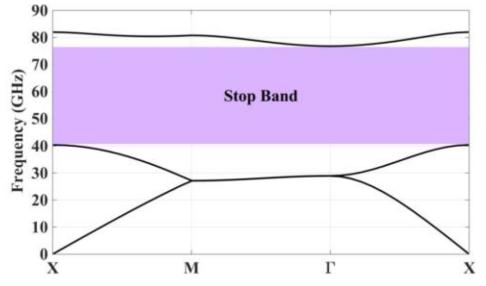
- M. Ebrahimpouri, E. Rajo-Iglesias, Z. Sipus, O. Quevedo-Teruel, "Cost-effective Integrated Waveguide Circuits Based on Glide-Symmetry Holey EBG Structure", *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 2, pp. 927-934, Feb. 2018.

EBG: Motivation

- Attenuation levels:



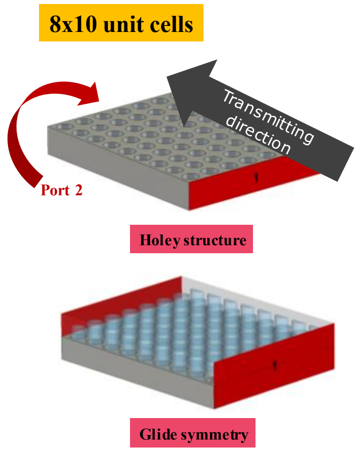


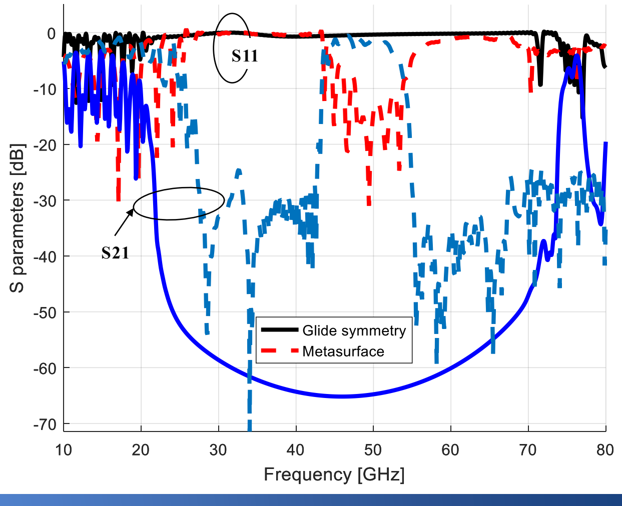


- M. Ebrahimpouri, E. Rajo-Iglesias, Z. Sipus, O. Quevedo-Teruel, "Cost-effective Integrated Waveguide Circuits Based on Glide-Symmetry Holey EBG Structure", *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 2, pp. 927-934, Feb. 2018.

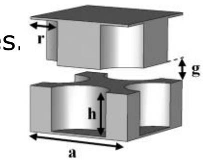
EBG: Comparison

- Conventional holey structure versus glide symmetry:

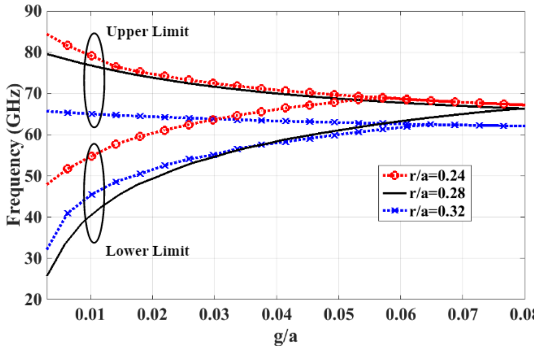


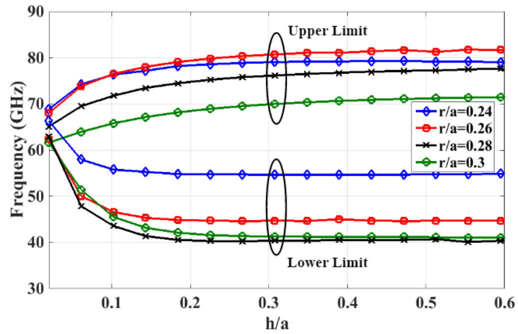


EBG: Properties



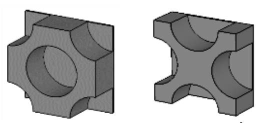
- To design a bandgap technology at low cost for high frequencies.
  - Large dimensions of holes.
  - Low dependence with depth (h).



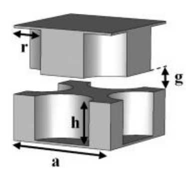


- M. Ebrahimpouri, O. Quevedo-Teruel, E. Rajo-Iglesias, "Design Guidelines for Gap Waveguide Technology Based on Glide-Symmetric Holey Structures", *IEEE Microwave and Wireless Component Letters,* vol. 27, no. 6, pp. 542-544, June 2017.

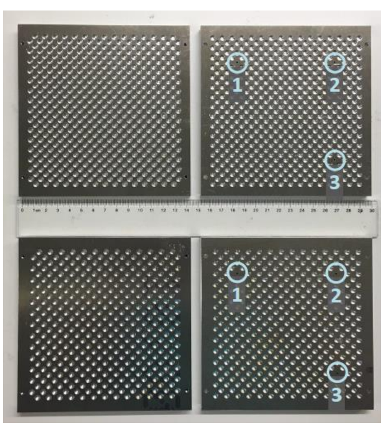
EBG: Demonstrator



Upper plate Lower plate

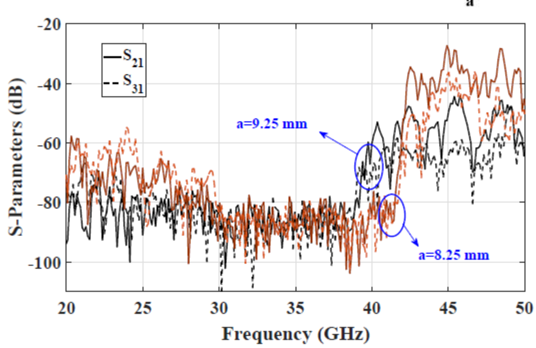


- Prototypes:



2r = 4.5 mm
h = 2 mm
g = 0.18 mm

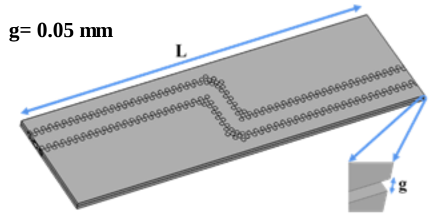
Two periodicities:
- a = 8.25 mm
- a = 9.25 mm

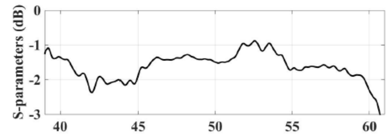


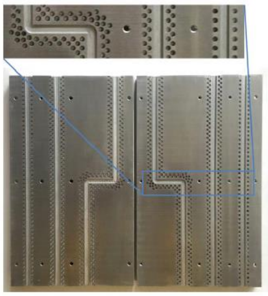
- M. Ebrahimpouri, O. Quevedo-Teruel, E. Rajo-Iglesias, "Design Guidelines for Gap Waveguide Technology Based on Glide-Symmetric Holey Structures", *IEEE Microwave and Wireless Component Letters,* vol. 27, no. 6, pp. 542-544, June 2017.

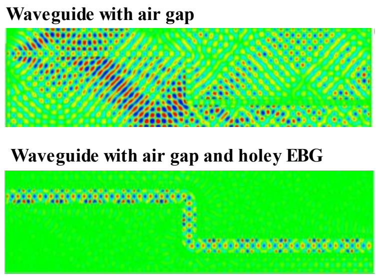
EBG: Examples

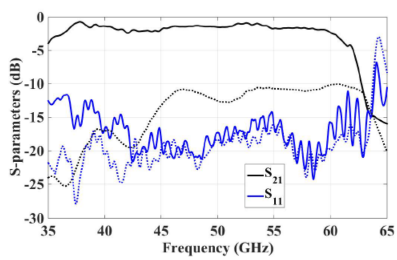
- This technology can be employed to design a number of electromagnetic components:
  - Waveguides.







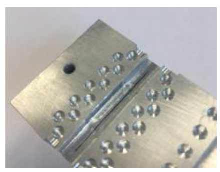




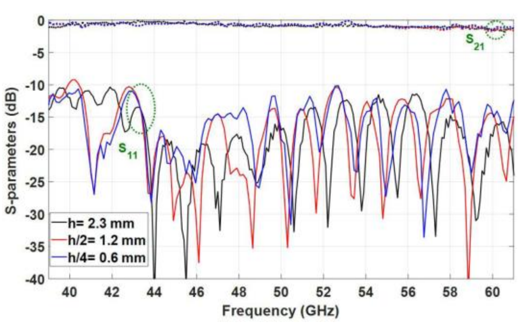
- M. Ebrahimpouri, E. Rajo-Iglesias, Z. Sipus, O. Quevedo-Teruel, "Cost-effective Integrated Waveguide Circuits Based on Glide-Symmetry Holey EBG Structure", *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 2, pp. 927-934, Feb. 2018.

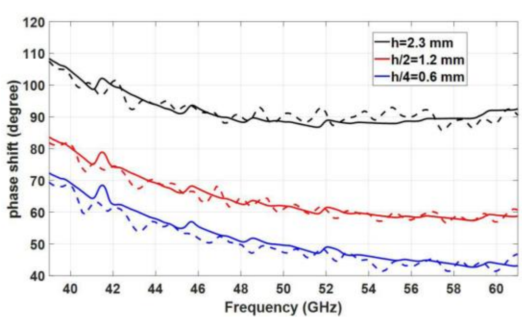
EBG: Phase shifter

- Broadband response
- Low losses.



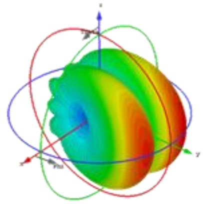
Using different heights for the dielectric layer



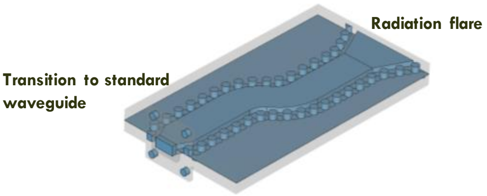


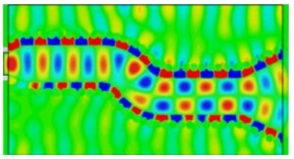
- E. Rajo-Iglesias, M. Ebrahimpouri, O. Quevedo-Teruel, "Wideband phase shifter in groove gap waveguide technology implemented with glide-symmetric holey EBG", *IEEE Microwave and Wireless Component Letters,* vol. 28, no. 6, pp. 476-478, June 2018.

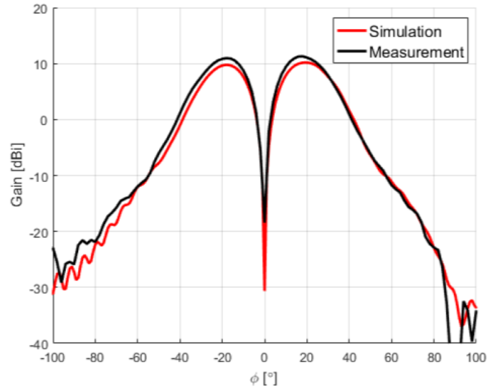
EBG: Mode converter



- Electromagnetic components:
  - Mode converter + differential mode radiation.



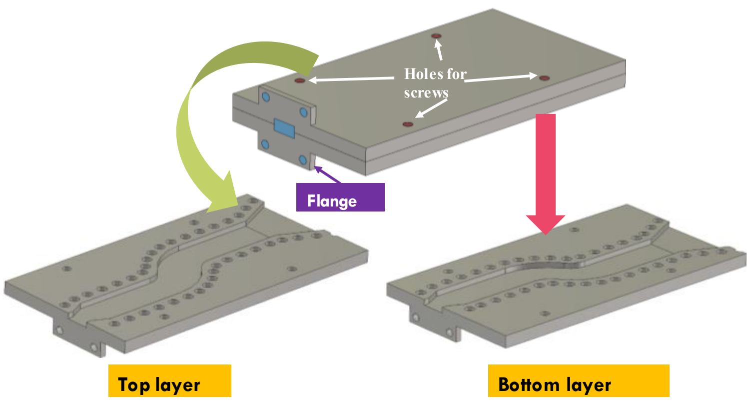


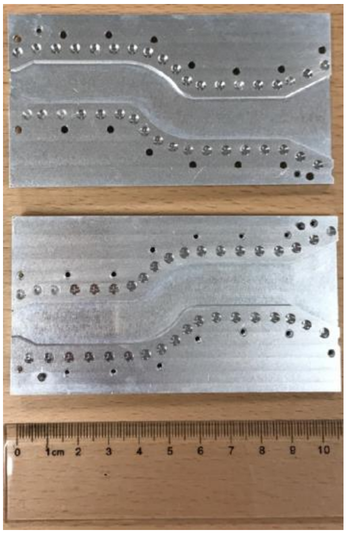


- Q. Liao, E. Rajo-Iglesias, O. Quevedo-Teruel, “Ka-band Fully Metallic TE40 Slot Array Antenna with Glide-symmetric Gap Waveguide Technology”, *Transactions on Antennas and Propagation*, 2019.

EBG: Mode converter

- Easy assembling.

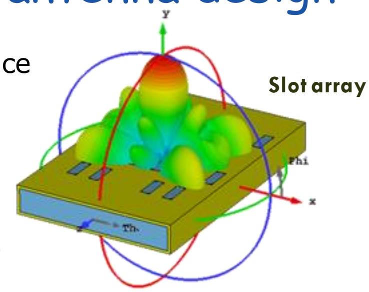


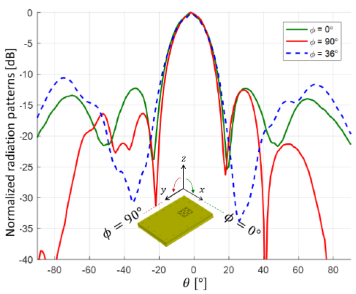


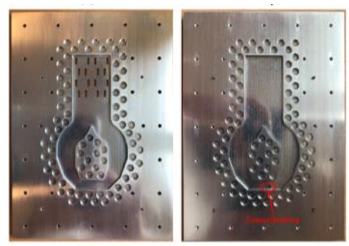
- Q. Liao, E. Rajo-Iglesias, O. Quevedo-Teruel, “Ka-band Fully Metallic TE40 Slot Array Antenna with Glide-symmetric Gap Waveguide Technology”, *IEEE Transactions on Antennas and Propagation*, 2019.

EBG: Mode converter for antenna design

- Two mode converters can be combined to produce a slot array of 4 elements with no grating lobes:



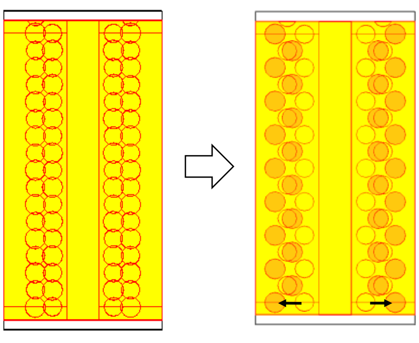


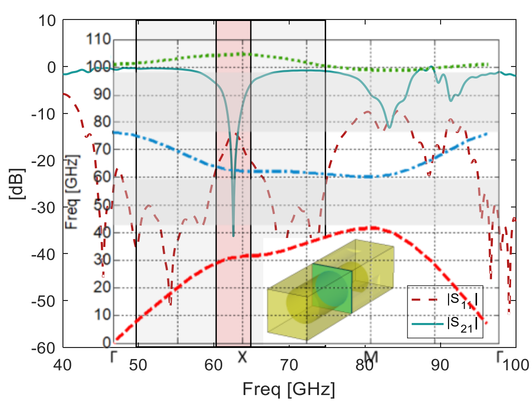


- Q. Liao, E. Rajo-Iglesias, O. Quevedo-Teruel, "Ka-band Fully Metallic TE40 Slot Array Antenna with Glide-symmetric Gap Waveguide Technology", *IEEE Transactions on Antennas and Propagation*, 2019.

Integrated filters

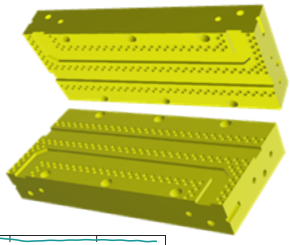
- By breaking the symmetry, it is posible to allow the propagation of waves in the parallel plate at selected frequencies.



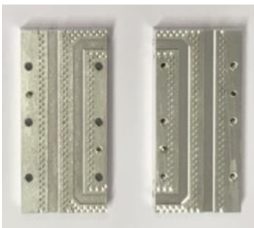


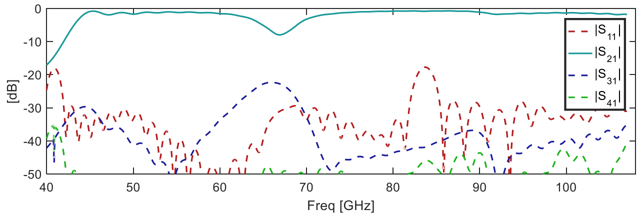
- P. Padilla, A. Palomares-Caballero, A. Alex-Amor, J. Valenzuela-Valdes, J. M. Fernandez-Gonzalez and O. Quevedo-Teruel, "Broken Glide-Symmetric Holey Structures for Bandgap Selection in Gap-Waveguide Technology," *IEEE Microwave and Wireless Components Letters*, vol. 29, no. 5, pp. 327-329, May 2019.

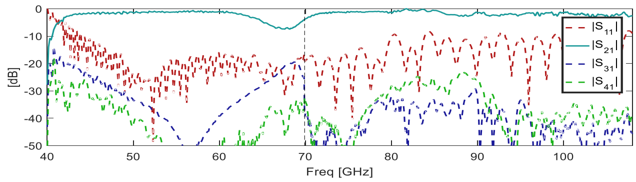
Integrated filters: Design



- Demonstrator in U-band: Rejected band at 65 GHz.







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EBG: Flanges

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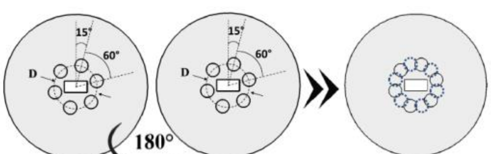
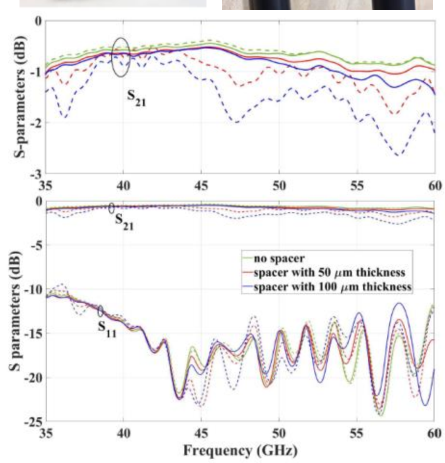
- Connections at high frequency:
  - Future integration in commercial flanges.
  - Idea is patented by Ericsson.





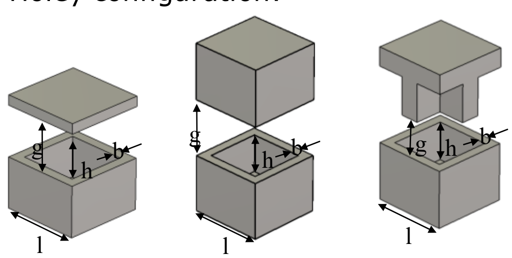
- M. Ebrahimpouri, A. Algaba Brazalez, L. Manholm, O. Quevedo-Teruel, "Using Glide-symmetric Holes to Reduce Leakage between Waveguide Flanges", *IEEE Microwave and Wireless Component Letters*, vol. 28, no. 6, pp. 473-475, June 2018.

Outline

- Definition of higher symmetries:
  - Why should we study higher symmetries?
- Modelling of higher-symmetric structures:
  - Circuit models.
  - Mode matching.
- Applications of glide-symmetric structures:
  - EBG structures:
    - Gap waveguide technology.
    - Flanges.
  - Ultra wide band lenses.
  - CPW and leaky waves.
  - Microstrip technology and filters.
- Twist symmetries.
- Conclusions

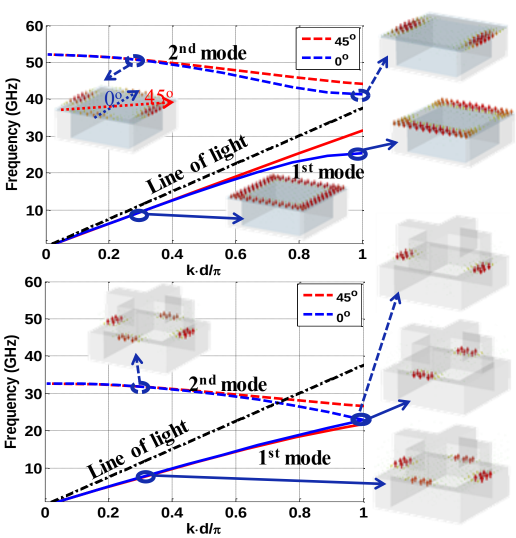
Dispersion properties:

- Holey configuration:



l = 4 mm, b = 0.5 mm,
h = 1.5 mm, g = 0.1 mm

- Very symmetric response with the double layered structure.
- Very good stability with frequency.

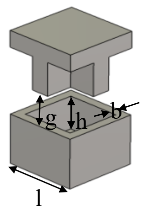


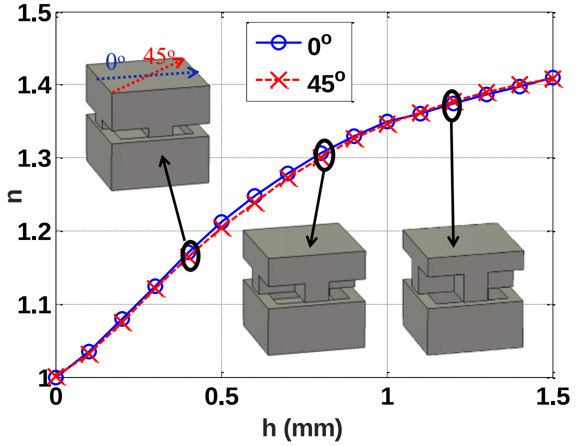
- O. Quevedo-Teruel, M. Ebrahimpouri, M. Ng Mou Kehn, "Ultra wide band metasurface lenses based on off-shifted opposite layers," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 484-487, 2016.

Refractive index: design curves

- Design as a function of the height (h) of the holes:

l = 4 mm
b = 0.5 mm
g = 0.1 mm





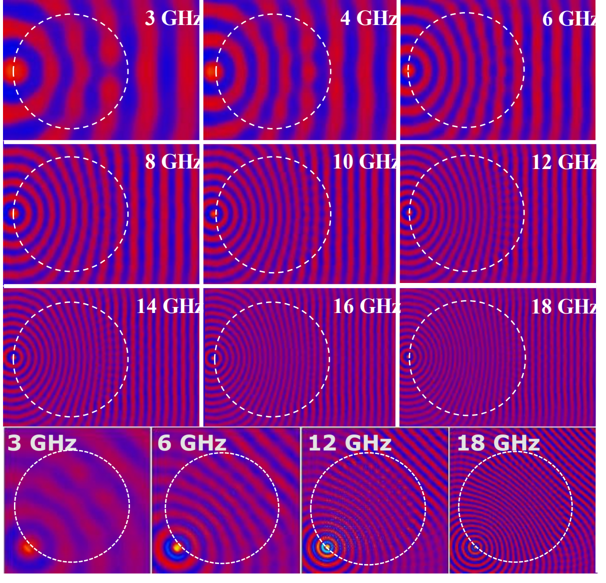
- Key features:
  - Stable with frequency:
    - ✓ Low dispersion
  - Symmetric response:
    - ✓ Almost isotropic.
  - Low values of refractive index in parallel plate:
    - ✓ Good transition to radiation.

- O. Quevedo-Teruel, M. Ebrahimpouri, M. Ng Mou Kehn, "Ultra wide band metasurface lenses based on off-shifted opposite layers," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 484-487, 2016.

Results: Luneburg lens

- Ultra-wide band response demonstrated from 3GHz to 18GHz:

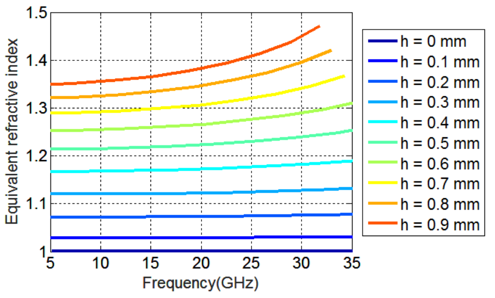
- Electric field distribution:
  - Point source to plane wave transformation.

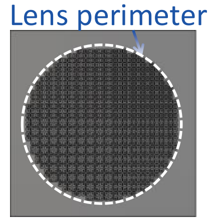


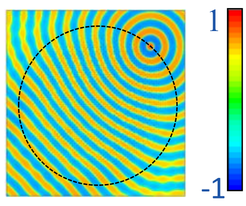
- O. Quevedo-Teruel, M. Ebrahimpouri, M. Ng Mou Kehn, "Ultra wide band metasurface lenses based on off-shifted opposite layers," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 484-487, 2016.

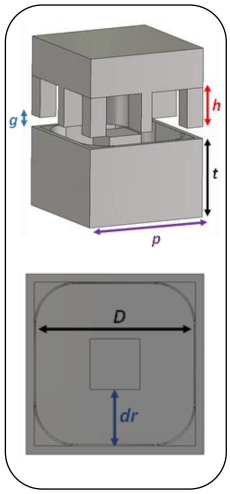
Results: Luneburg lens (Ka-band)

- Unit cell configuration:
  - Glide-symmetric holes loaded with pins





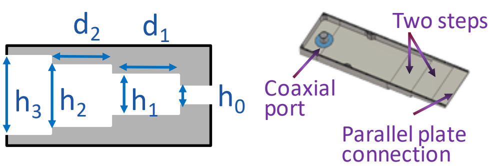


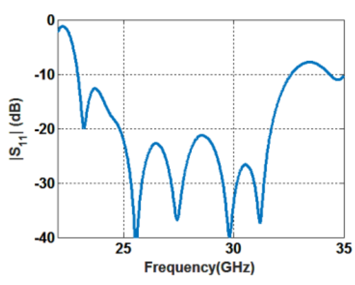


- O. Quevedo-Teruel, J. Miao, M. Mattsson, A. Algaba-Brazalez, M. Johansson, L. Manholm, "Glide-symmetric fully-metallic Luneburg lens for 5G Communications at Ka-band", *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 9, pp. 1588-1592, Sept. 2018.

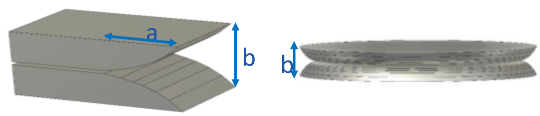
Luneburg lens (Ka-band)

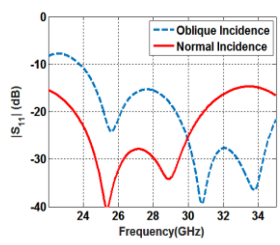
- Feeding design:

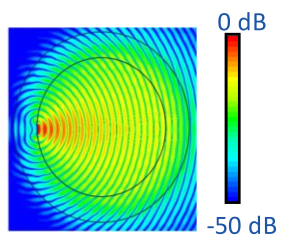




- Flare design:







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Measurements

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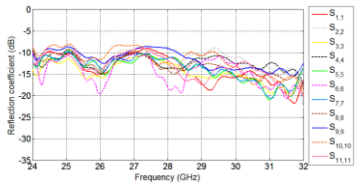
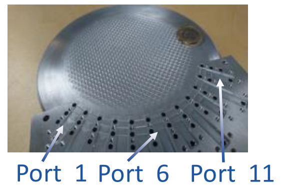
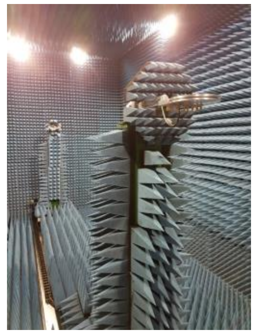
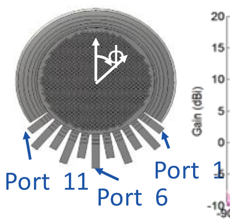
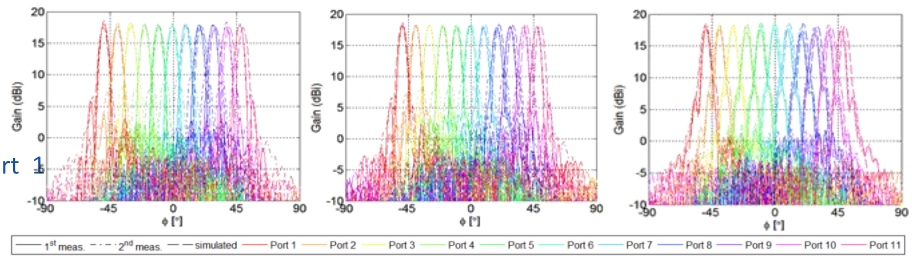
- Good agreement with the simulations











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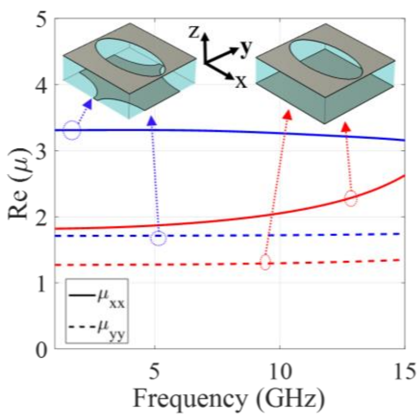
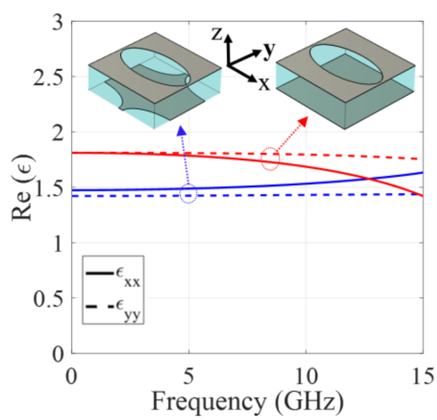
Compressed lenses: Anisotropy

- Broad band anisotropy is also possible to achieve with glide symmetry:





- M. Ebrahimpouri, O. Quevedo-Teruel, "Ultra-wideband Anisotropic Glide-symmetric Metasurfaces", *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 8, pp. 1547-1551, Aug. 2019.

Compressed lenses: Transformation optics

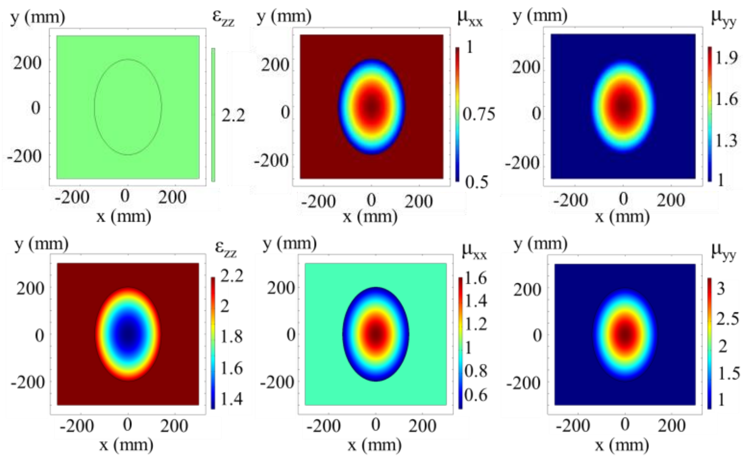
- Using transformation optics, we can compress the space:

$$\overline{\overline{\varepsilon'}} = \varepsilon \begin{bmatrix} 1/\alpha & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & \alpha \end{bmatrix}$$

$$\overline{\overline{\mu'}} = \mu \begin{bmatrix} 1/\alpha & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & \alpha \end{bmatrix}$$

$$\varepsilon = \varepsilon_0$$

$$\mu = \mu_0 \left(2 - \frac{(\alpha x')^2 + y'^2}{R^2}\right)$$



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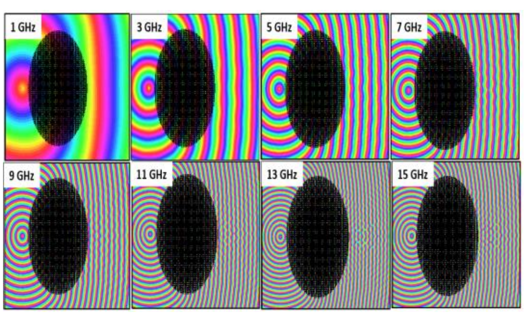
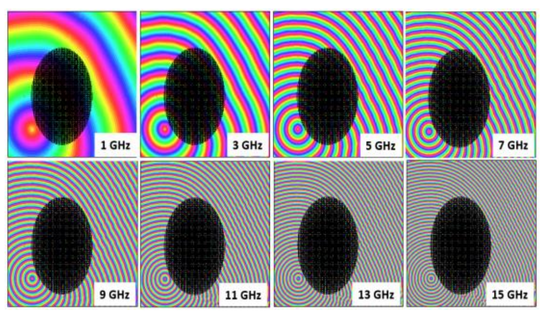
Implementation in printed technology

- Main direction:
- 45 degrees:





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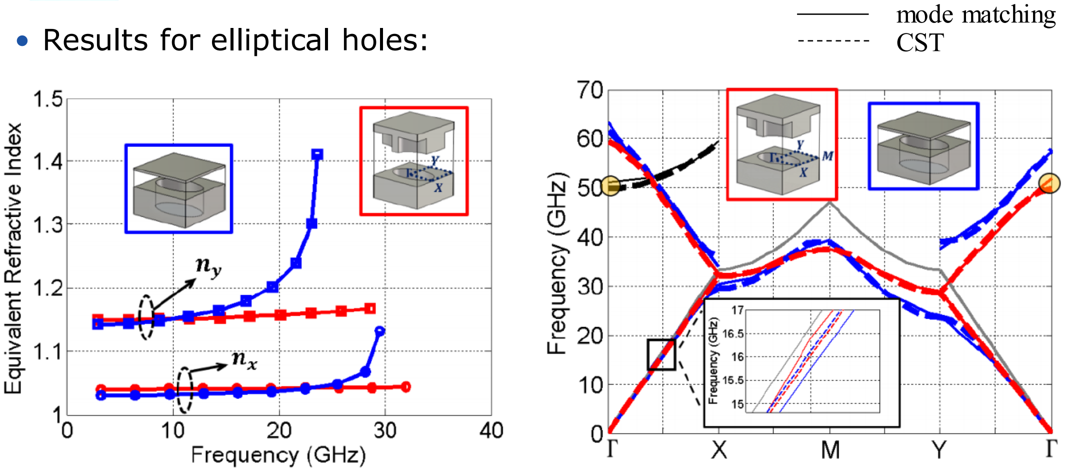
Fully metallic unit cells

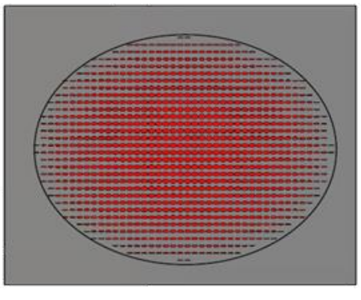
- Results for elliptical holes:

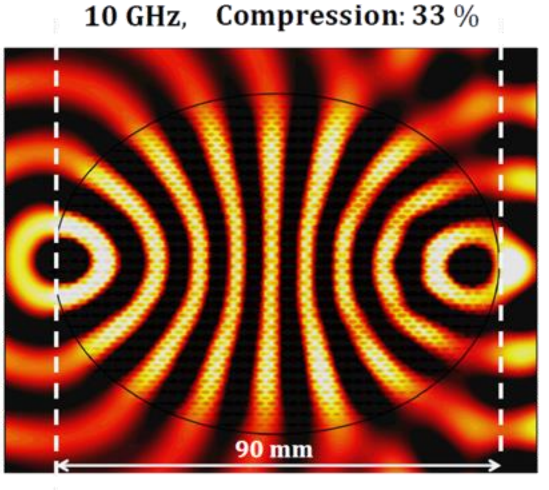


- A. Alex-Amor, F. Ghasemifard, G. Valerio, P. Padilla, J. M. Fernandez-Gonzalez, O. Quevedo-Teruel, "Glide-Symmetric Metallic Structures with Elliptical Holes", *submitted to IEEE Transactions on Microwave Theory and Techniques.*

Lens compression with anisotropy

- Lens compression of a Maxwell fish eye lens:





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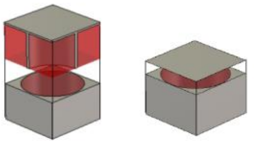
Mode-matching: Anisotropy

- Lens compression:

$n_{\text{Glide}}^{MAX} = 2.86 \Rightarrow \beta_{\text{Glide}}^{MAX} = 43\%$

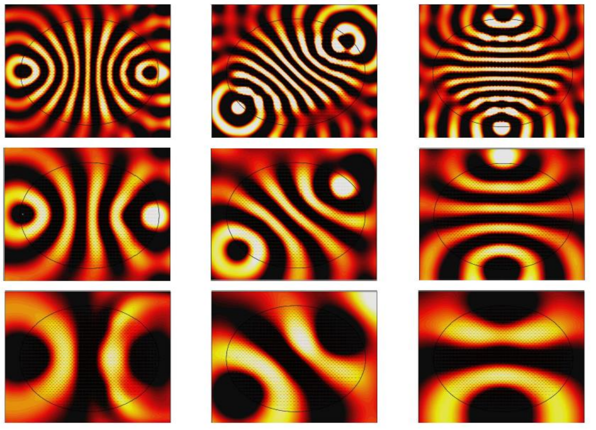


$n_{\text{Non-Glide}}^{MAX} = 2.05 \Rightarrow \beta_{\text{Non-Glide}}^{MAX} = 3.5\%$

10 GHz

5 GHz

2.5 GHz



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  - EBG structures:
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  - CPW and leaky waves.
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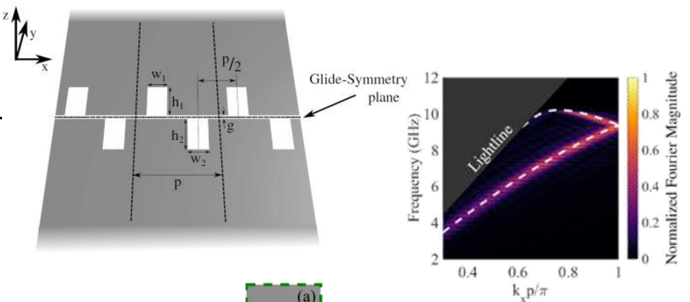
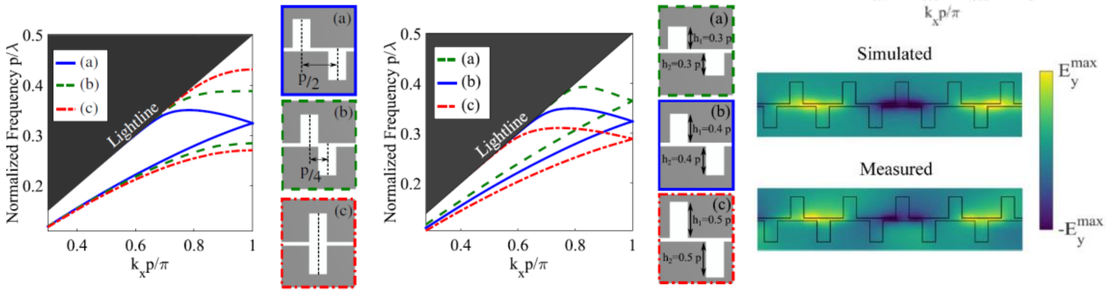
Slotted lines

- One slot with glide-symmetric orthogonal holes.

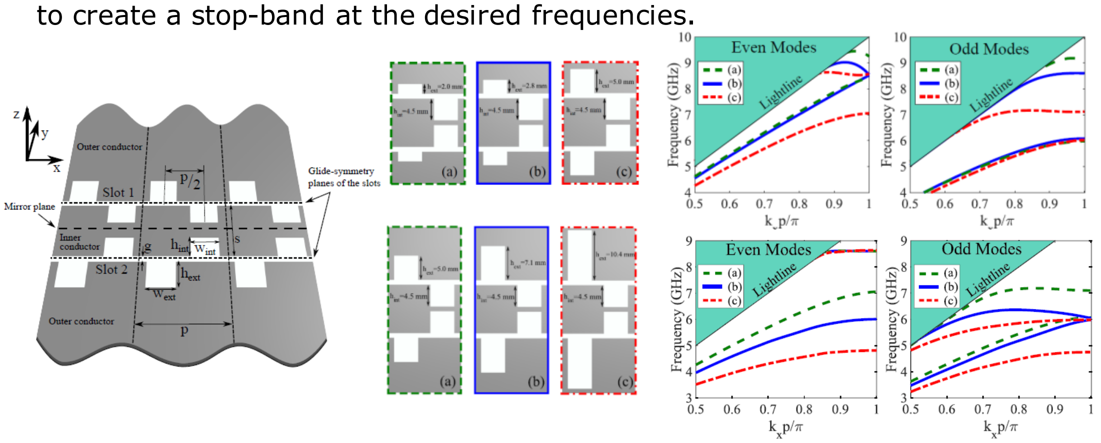




- M. Camacho, R. C. Mitchell-Thomas, A. P. Hibbins, J. Roy Sambles, and O. Quevedo-Teruel, "Designer surface plasmon dispersion on a one-dimensional periodic slot metasurface with glide symmetry", *Optics Letters*, Vol. 42, No. 17, pp: 3375-3378, 2017.

CPW technology: Simulations

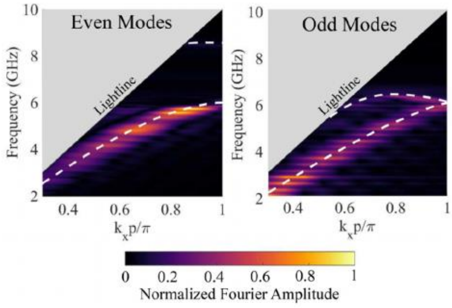
- Two symmetric coupled CPW, each one loaded with transverse stubs
- Tuning the asymmetries between the stubs leads to mimic glide-symmetry or to create a stop-band at the desired frequencies.

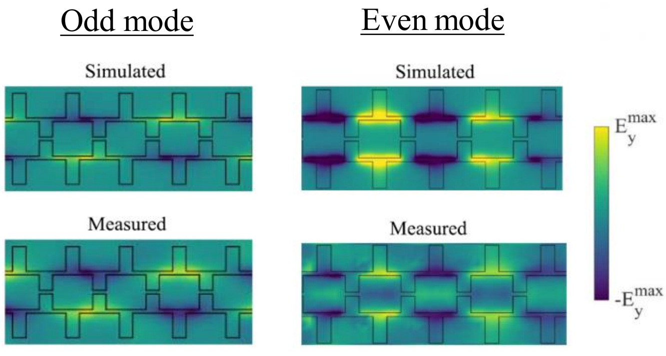


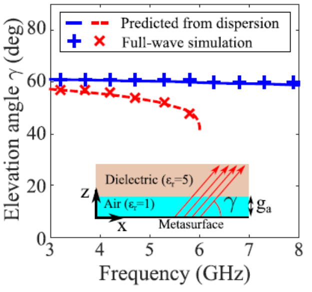
- M. Camacho, R. C. Mitchell-Thomas, A. P. Hibbins, J. Roy Sambles, and O. Quevedo-Teruel, "Mimicking glide symmetry dispersion with coupled slot metasurfaces," *Applied Physics Letters*, vol. 111, no. 12, p. 121603, 2017.

CPW: Measurements

- Measured dispersion properties.
- Radiation properties with a dielectric.







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  - CPW and leaky waves.
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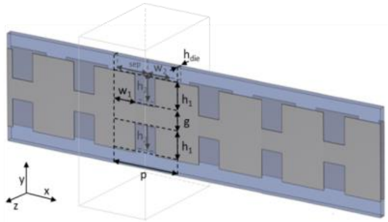
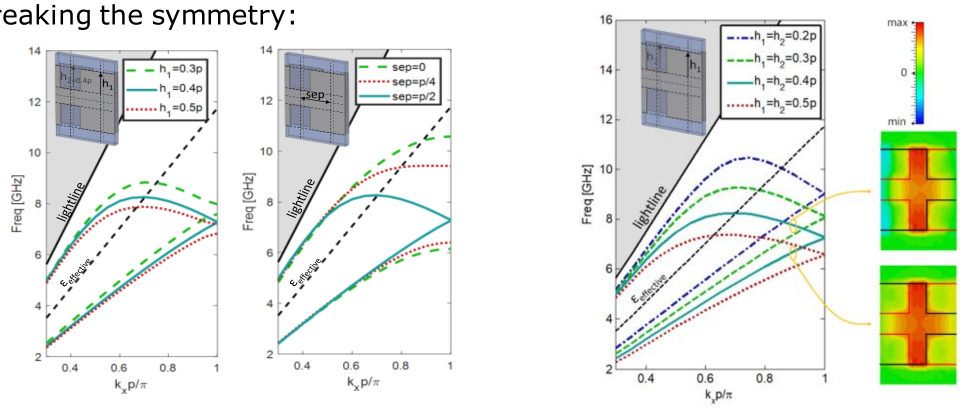
Printed bifilar technology



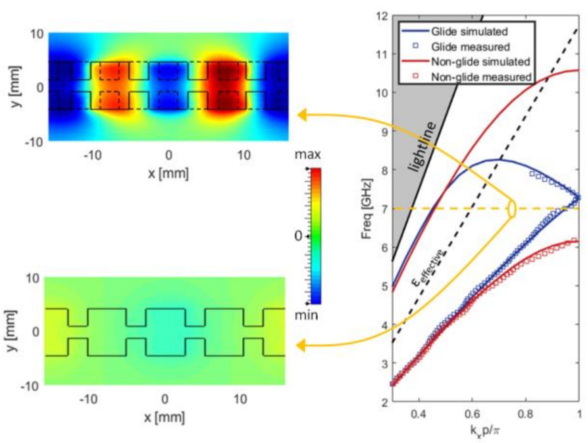
- Two printed bifilar lines on top and bottom of a dielectric substrate.
- Breaking the symmetry:

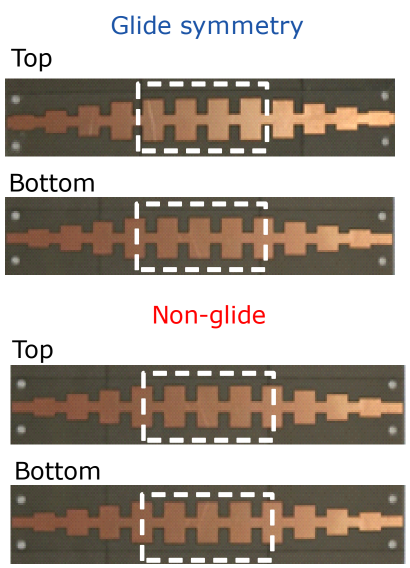


- P. Padilla, L. F. Herran, A. Tamayo-Dominguez, J. F. Valenzuela-Valdes, O. Quevedo-Teruel, "Glide symmetry to prevent the lowest stopband of printed transmission lines", *IEEE Microwave and Wireless Component Letters*, vol. 28, no. 9, pp. 750-752, Sept. 2018.

Bifilar: Measurements

- Measurement results: Dispersion.

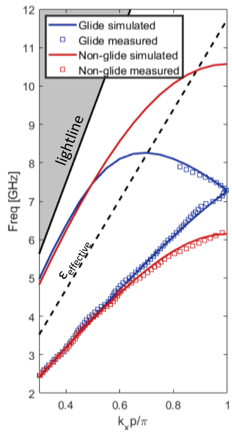


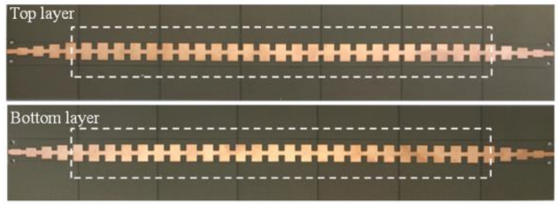


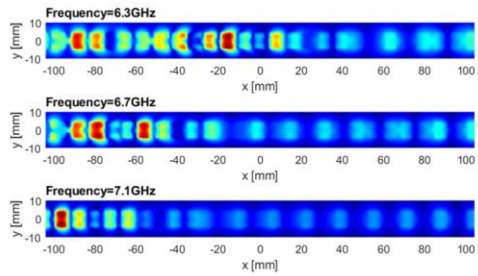
- P. Padilla, L. F. Herran, A. Tamayo-Dominguez, J. F. Valenzuela-Valdes, O. Quevedo-Teruel, "Glide symmetry to prevent the lowest stopband of printed transmission lines", *IEEE Microwave and Wireless Component Letters*, vol. 28, no. 9, pp. 750-752, Sept. 2018.

Printed bifilar technology: filtering properties

- Measurement results: Filtering.



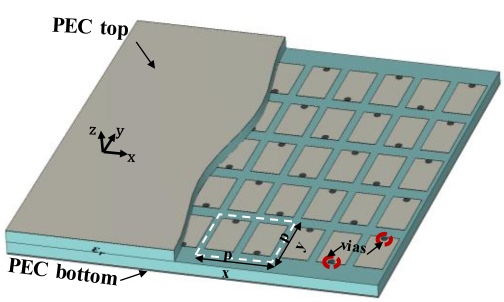


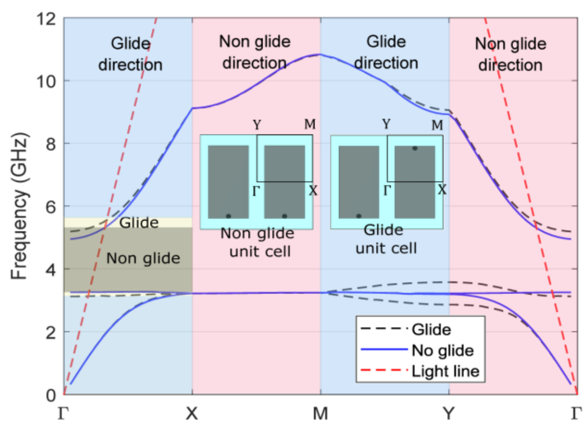


- P. Padilla, L. F. Herran, A. Tamayo-Dominguez, J. F. Valenzuela-Valdes, O. Quevedo-Teruel, "Glide symmetry to prevent the lowest stopband of printed transmission lines", *IEEE Microwave and Wireless Component Letters*, vol. 28, no. 9, pp. 750-752, Sept. 2018.

Planar stop-band: Dispersion diagrams

- Microstrip technology: Planar stop-bands.

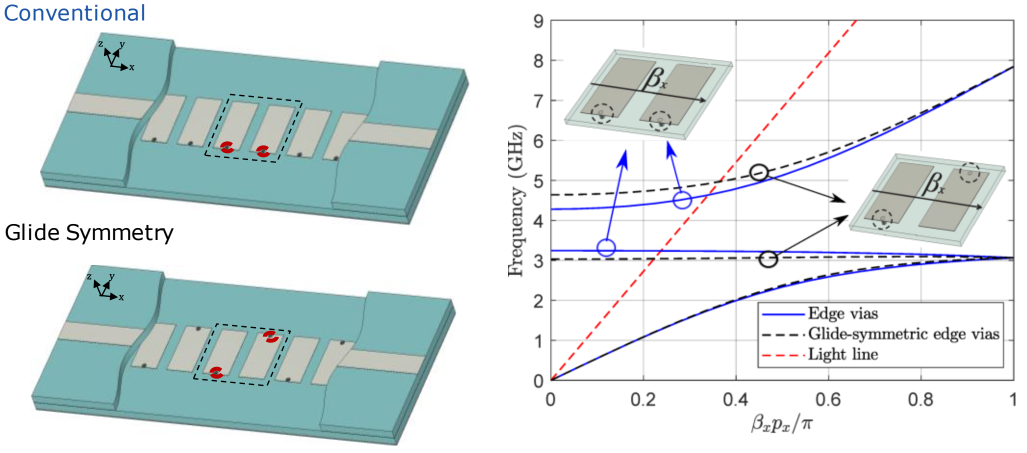




- B. A. Mouris, A. Fernandez-Prieto, R. Thobaben, J. Martel, F. Mesa, O. Quevedo-Teruel, "On the Increment of the Bandwidth of Mushroom-type EBG Structures with Glide Symmetry", *submitted to IEEE Transactions on Microwave Theory and Techniques*.

Planar stop-band: Dispersion diagrams

- Microstrip technology: Planar stop-bands.



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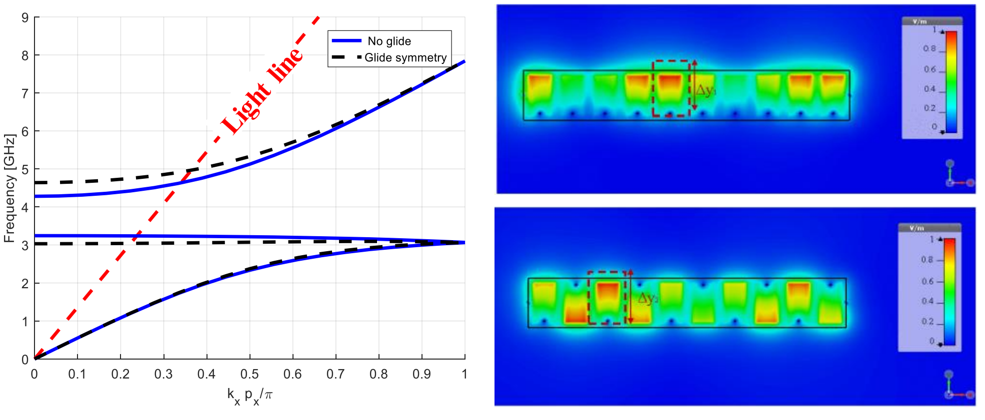
Planar stop-band: Confinement

- The higher frequency cut-off is due to the confinement of the fields:



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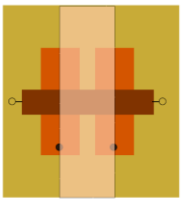
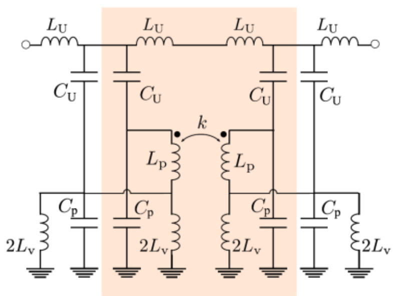
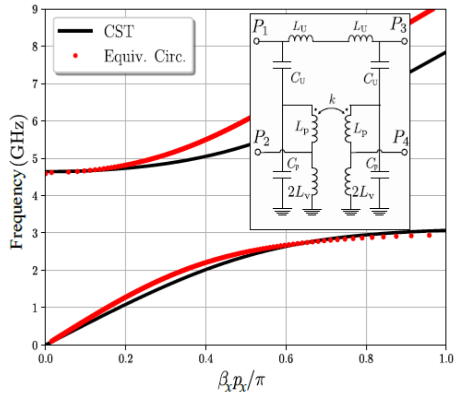
Planar stop-band: Circuit model

- Mutual coupling between elements is different.
- Coupling is mainly inductive.



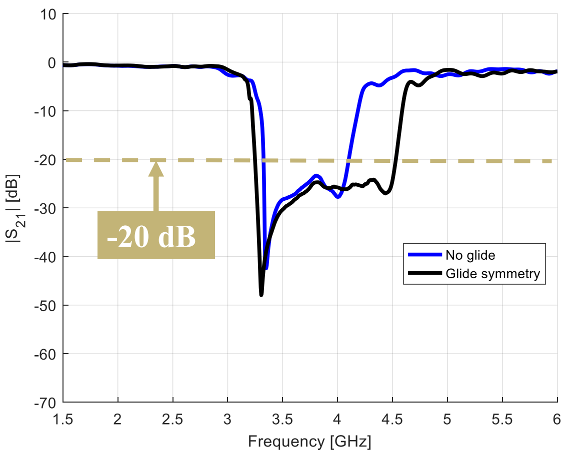




- B. A. Mouris, A. Fernandez-Prieto, R. Thobaben, J. Martel, F. Mesa, O. Quevedo-Teruel, "On the Increment of the Bandwidth of Mushroom-type EBG Structures with Glide Symmetry", *submitted to IEEE Transactions on Microwave Theory and Techniques.*

Planar stop-band: Measurements

- The measurements corroborate the simulated results:



Approx. 67% BW improvement in the measurements

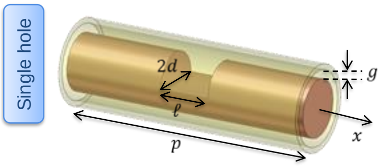
- B. A. Mouris, A. Fernandez-Prieto, R. Thobaben, J. Martel, F. Mesa, O. Quevedo-Teruel, "On the Increment of the Bandwidth of Mushroom-type EBG Structures with Glide Symmetry", *submitted to IEEE Transactions on Microwave Theory and Techniques.*

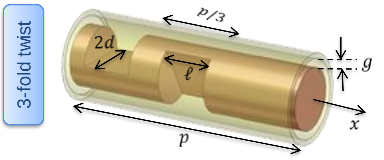
Outline

- Definition of higher symmetries:
  - Why should we study higher symmetries?
- Modelling of higher-symmetric structures:
  - Circuit models.
  - Mode matching.
- Applications of glide-symmetric structures:
  - EBG structures:
    - Gap waveguide technology.
    - Flanges.
  - Ultra wide band lenses.
  - CPW and leaky waves.
  - Microstrip technology and filters.
- Twist symmetries.
- Conclusions

Twist-symmetric periodic structures

$$S_m \equiv \begin{cases} x \to x + \dfrac{p}{m} \\ \varphi \to \varphi + \dfrac{2\pi}{m} \end{cases}$$





Oliner's generalized Floquet theorem for an m-fold twist-symmetric structure

$$\mathcal{S}_m[\mathbf{E}(\rho,\varphi,z)] = \mathbf{E}\left(\rho + \frac{d}{m}, \varphi + \frac{2\pi}{m}, z\right) = e^{-jk_x p/m}\mathbf{E}(\rho,\varphi,z)$$

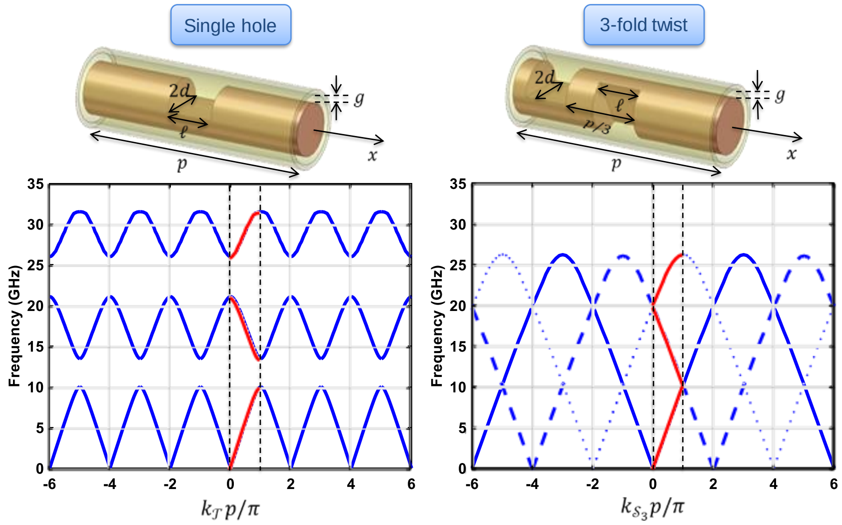
$k_{\mathcal{S}_m}(\omega)p$ is peridic with period $2m\pi$

$$k_{\mathcal{S}_m}(\omega)p = k_{\mathcal{S}_{m,0}}(\omega)p + 2mn\pi$$

$$-m\pi < k_{\mathcal{S}_{m,0}}(\omega)p < m\pi$$

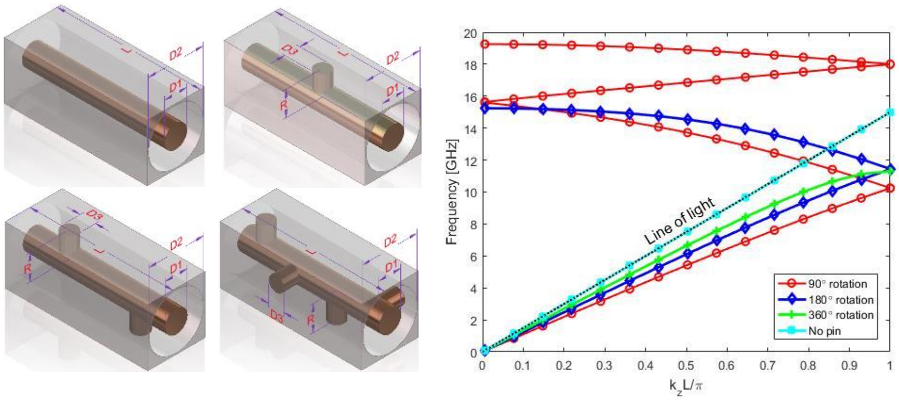
$$k_{\mathcal{T}}(\omega)p = k_{\mathcal{S}_m}(\omega)p + 2\pi\nu \quad \nu = 0,1,\dots,m-1$$

Generalized Floquet theorem



Twist symmetries: Metallic pins

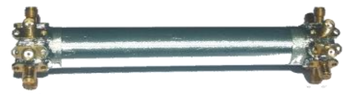
- Twist-symmetric metallic pins in a coaxial cable.

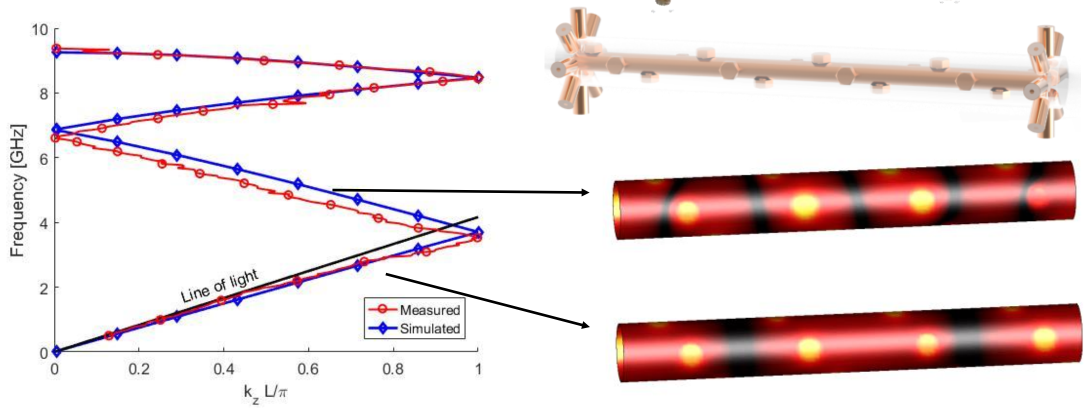


- O. Dahlberg, R. C. Mitchell-Thomas, O. Quevedo-Teruel, "Reducing the Dispersion of Periodic Structures with Twist and Polar Glide Symmetries", *Scientific Reports*, vol. 7, article number 10136, 2017.

Twist symmetries: Measurements

- Forward modes.
- No band-gaps: Perfect symmetry



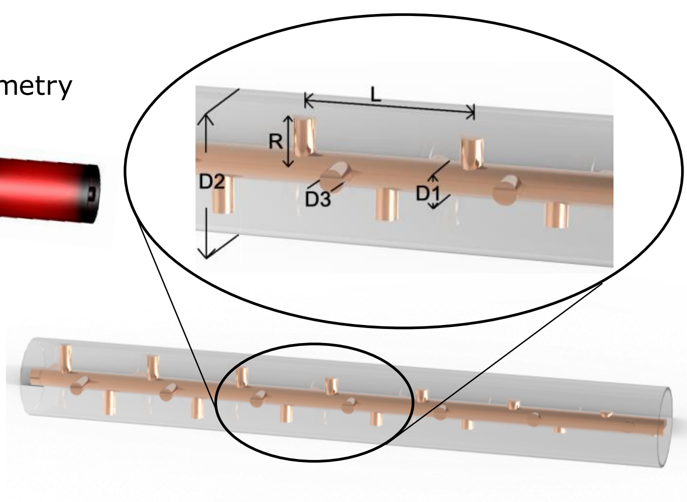


- O. Dahlberg, R. C. Mitchell-Thomas, O. Quevedo-Teruel, "Reducing the Dispersion of Periodic Structures with Twist and Polar Glide Symmetries", *Scientific Reports*, vol. 7, article number 10136, 2017.

Twist symmetries: Variable refractive index

- Forward modes.
- No band-gaps: Perfect symmetry

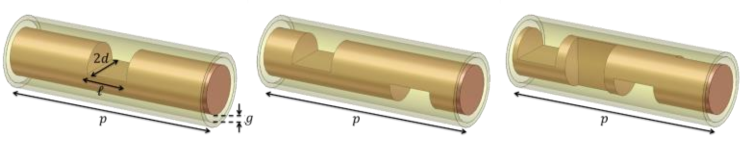
Label	Dim. [mm]
D1	2
D2	8
D3	1.4
R	3.8 – 0
L	10
Airgap	0.2 – 4

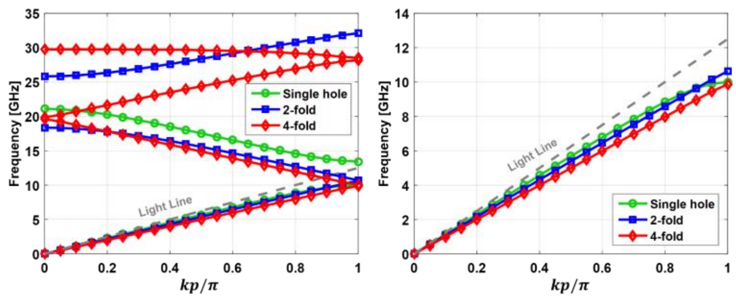


- O. Dahlberg, R. C. Mitchell-Thomas, O. Quevedo-Teruel, "Reducing the Dispersion of Periodic Structures with Twist and Polar Glide Symmetries", *Scientific Reports*, vol. 7, article number 10136, 2017.

Twist symmetries: Holey structure

- Similar configuration to the pin-type but with holes.

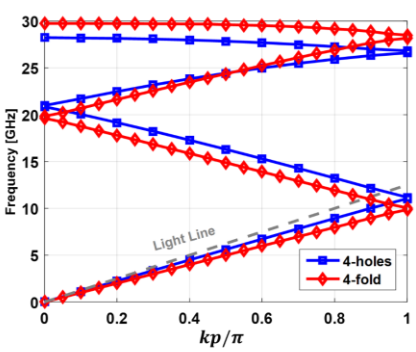


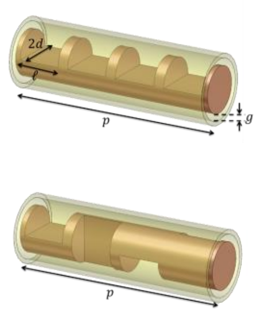


- F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, "Twist and Polar Glide Symmetries: an Additional Degree of Freedom to Control the Propagation Characteristics of Periodic Structures", *Scientific Reports*, vol. 8, Article number: 11266, 2018.

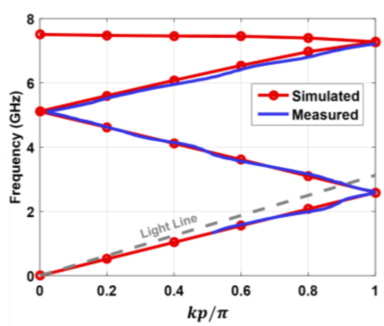
Holey twist symmetries: Operation

- Twist versus non-twist:





- Measurement results:



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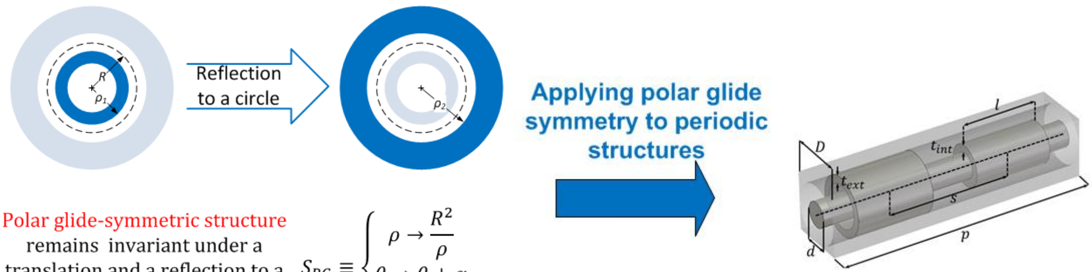
Polar glide symmetry

- Coaxial cable with rings inside and outside metallic conductors.
- Similar approach of transformation optics.

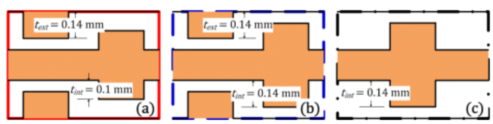


Polar glide-symmetric structure remains invariant under a translation and a reflection to a circular or cylindrical surface

$$S_{PG} \equiv \begin{cases} \rho \rightarrow \dfrac{R^2}{\rho} \\ \theta \rightarrow \theta + \alpha \\ z \rightarrow z + \dfrac{p}{2} \end{cases}$$

- Q. Chen, F. Ghasemifard, G. Valerio, O. Quevedo-Teruel, "Modeling and Dispersion Analysis of Coaxial Lines with Higher Symmetries" *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 10, pp. 4338-4345, Oct. 2018.

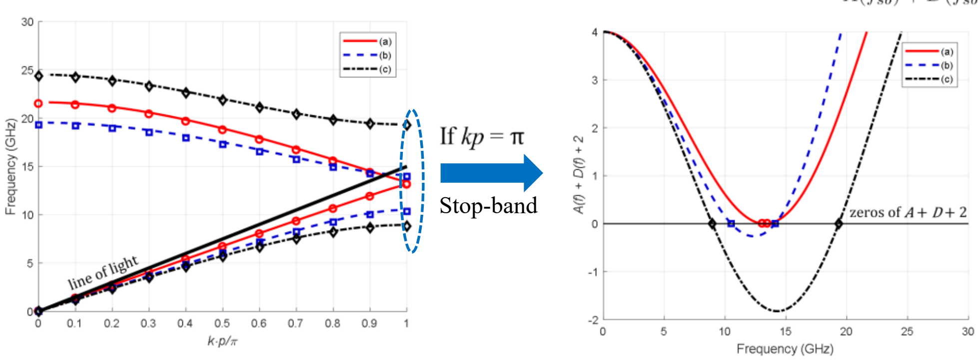
Polar glide symmetry



- Control of the stop-band in the propagation of the coaxial cable.
- Elimination of the first band-gap with polar gide.

$$\cos(kp) = \frac{A(f) + D(f)}{2},$$

$$A(f_{sb}) + D(f_{sb}) + 2 = 0.$$



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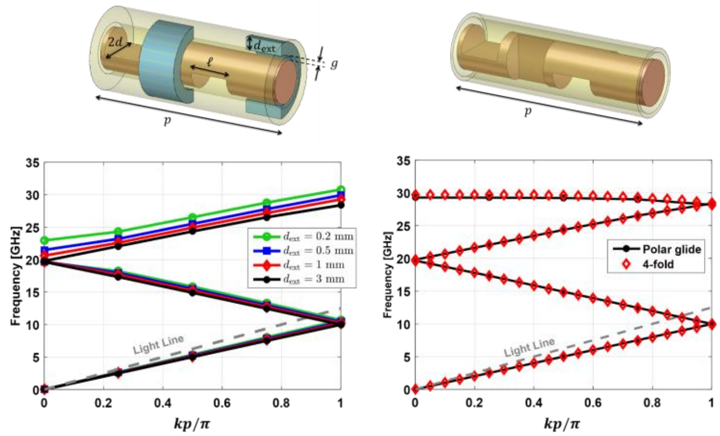
Holey twist symmetries: Polar glide

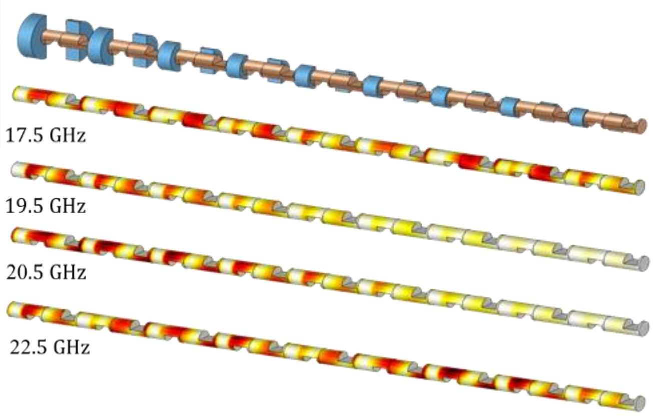
- Polar glide symmetry: Mimicking glide symmetry.

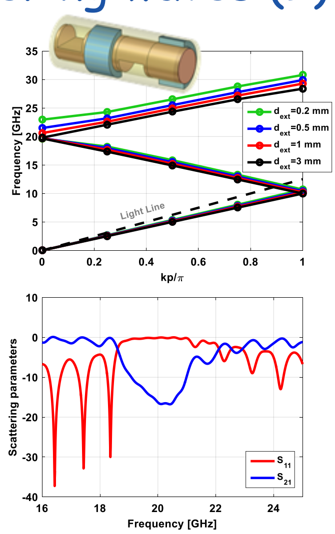


- F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, "Twist and Polar Glide Symmetries: an Additional Degree of Freedom to Control the Propagation Characteristics of Periodic Structures", *Scientific Reports*, vol. 8, Article number: 11266, 2018.

Holey twist symmetries: Filtering waves (I)

- Another possible application is to break the symmetry to filter the electromagnetic propagation.

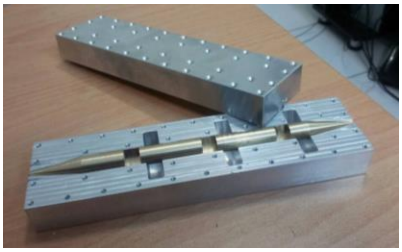


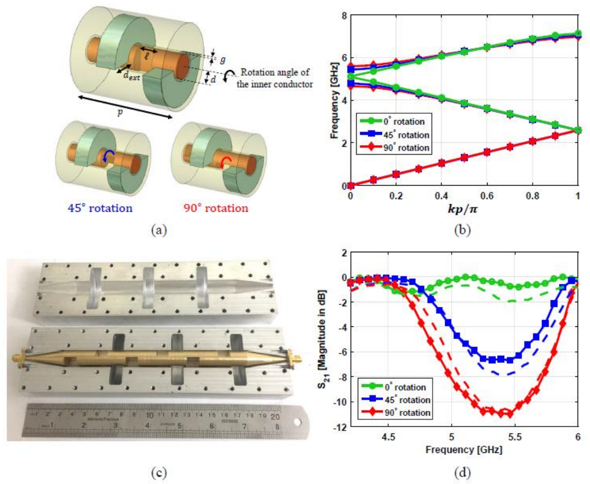


- F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, "Twist and Polar Glide Symmetries: an Additional Degree of Freedom to Control the Propagation Characteristics of Periodic Structures", *Scientific Reports*, vol. 8, Article number: 11266, 2018.

Holey twist symmetries: Filtering waves(II)

- Twisting inner conductor.
- Measurement results.



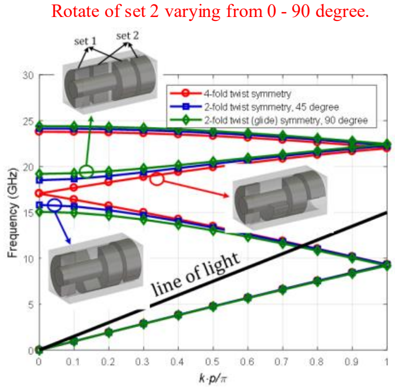


- F. Ghasemifard, M. Norgren, O. Quevedo-Teruel, "Twist and Polar Glide Symmetries: an Additional Degree of Freedom to Control the Propagation Characteristics of Periodic Structures", *Scientific Reports*, vol. 8, Article number: 11266, 2018.

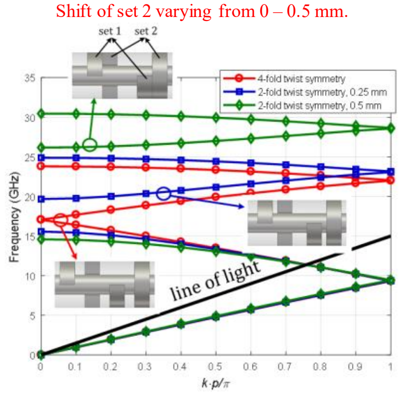
Twist symmetry

- This configuration can be extended to twist-symmetric section rings.

Rotate of set 2 varying from 0 - 90 degree.



Shift of set 2 varying from 0 – 0.5 mm.

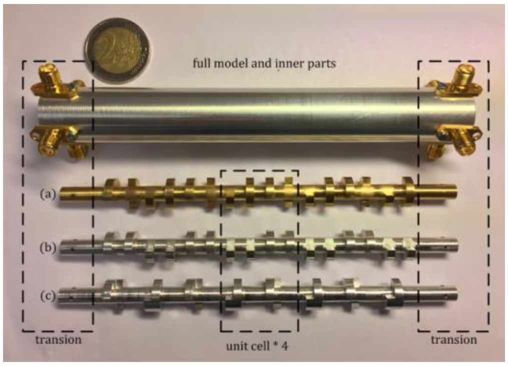


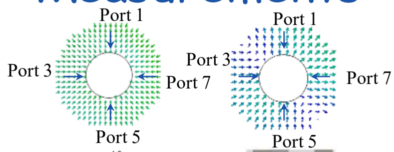
These modifications are equivalent to decreasing the order of 4-fold to 2-fold twist symmetry.

- Q. Chen, F. Ghasemifard, G. Valerio, O. Quevedo-Teruel, "Modeling and Dispersion Analysis of Coaxial Lines with Higher Symmetries" *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 10, pp. 4338-4345, Oct. 2018.

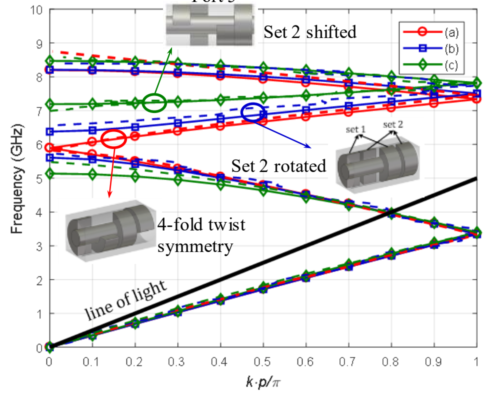
Twist symmetry: Measurements

- The configuration needs:
  - Remove of the connectors.
  - Different modes exicitation





For de-embedding

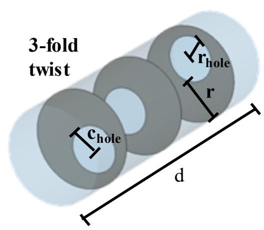


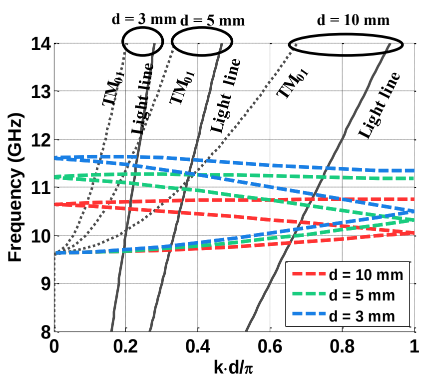
- Q. Chen, F. Ghasemifard, G. Valerio, O. Quevedo-Teruel, "Modeling and Dispersion Analysis of Coaxial Lines with Higher Symmetries" *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 10, pp. 4338-4345, Oct. 2018.

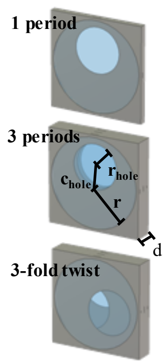
Waveguides: Vertical walls

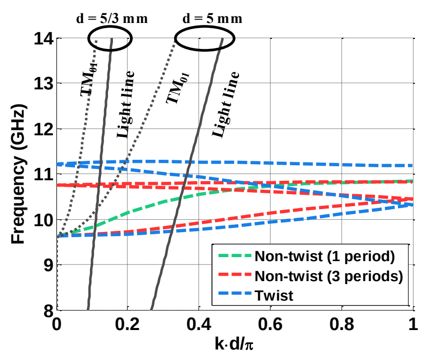
- Waveguide propagation:
  - Circular waveguide, for simplicity.
  - Propagation of *TM* modes.

$r_{hole} = r/2$
$r = 12$ mm
$c_{hole} = r/3$



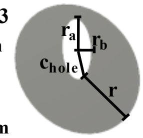




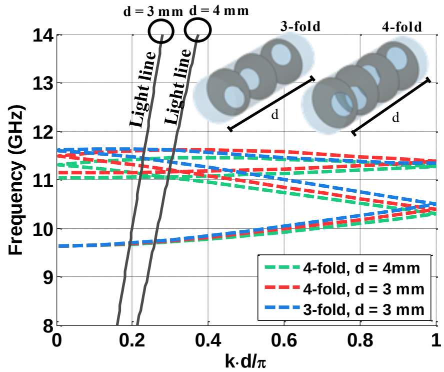


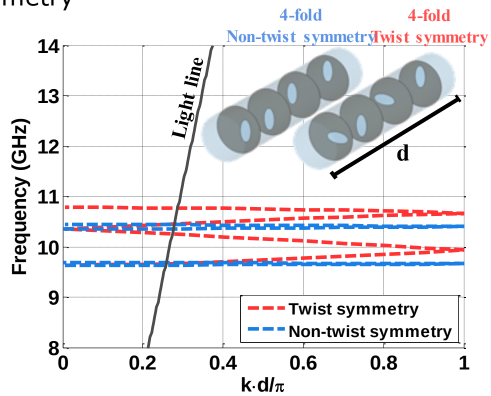
- O. Quevedo-Teruel, O. Dahlberg, G. Valerio, "Propagation in waveguides with transversal twist-symmetric holey metallic plates", *accepted in IEEE Microwave and Wireless Component Letters*, vol. 28, no. 10, pp. 858-860, Oct. 2018.

Waveguides: Propagation properties



- Waveguide propagation:
  - Fold number changes the propagation properties.
  - <u>Elliptical holes:</u> Importance of the symmetry





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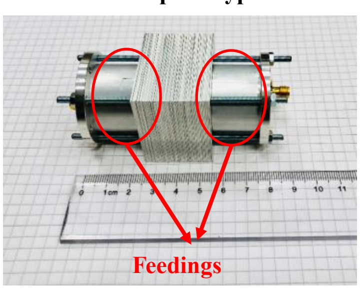
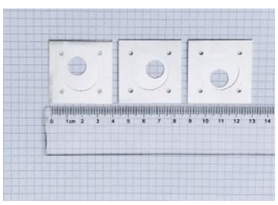
Waveguides: Experimental results

- Practical applications (fully metallic structures):
  - Compact phase shifters.
  - Tuneable filters.

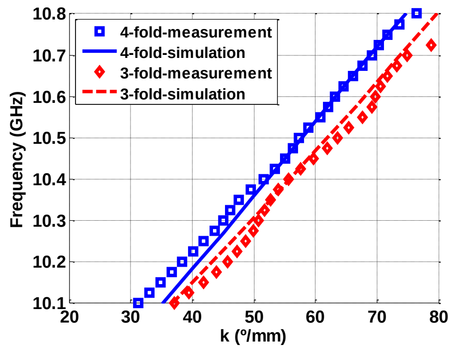
Full prototype



3-fold



120° rotation



- O. Quevedo-Teruel, O. Dahlberg, G. Valerio, "Propagation in waveguides with transversal twist-symmetric holey metallic plates", *accepted in IEEE Microwave and Wireless Component Letters*, vol. 28, no. 10, pp. 858-860, Oct. 2018.

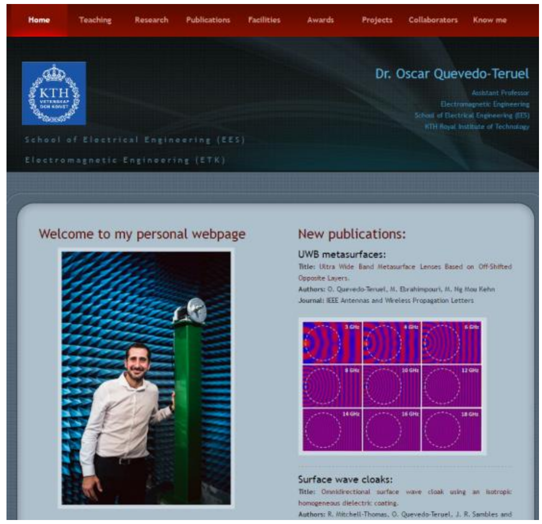
Outline

- Definition of higher symmetries:
  - Why should we study higher symmetries?
- Modelling of higher-symmetric structures:
  - Circuit models.
  - Mode matching.
- Applications of glide-symmetric structures:
  - EBG structures:
    - Gap waveguide technology.
    - Flanges.
  - Ultra wide band lenses.
  - CPW and leaky waves.
  - Microstrip technology and filters.
- Twist symmetries.
- Conclusions

Conclusions

- Here, we have explained the importance of higher-symmetric structures.
- Numerical and analytical methods are need for fast analysing these structures.
- Glide symmetry demonstrated to be a good candidate for:
  - **EBG structures:**
    - ✓ Easy of being manufactured due to the large dimensions: Gap waveguide and flanges.
  - **Lenses:**
    - ✓ Isotropic (anisotropic), low dispersive, low losses (air propagation): Lens antennas and compressed lenses.
  - **Transmission lines:**
    - ✓ Low dispersive CPW: Low dispersive leaky wave antennas.
    - ✓ Low dispersive printed bifilar lines: Filters and phase shifters.
    - ✓ Enhanced stop-bands: Microstrip filters.
- Twist symmetries studies are still preliminary, however they are good candidates for low dispersive and fully-metallic leaky wave antennas, filters, and phase shifters.

Thank you for your attention!



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