Inverse Design of Microwave Post-wall Waveguides-based Filters

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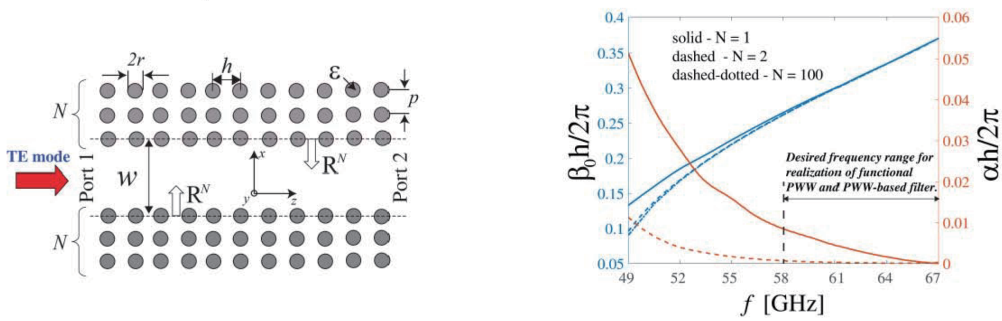
Abstract— Conventional rectangular waveguides developed several decades ago cannot be used for circuit and system integration because of their bulky mechanical and non-planar nature. An alternative to the conventional non-planar guiding devices is the Post-Wall Waveguide (PWW) [1, 2]. A transversal view of a typical configuration of the PWW is shown in Fig. 1(a). The EM fields of the PWW are confined in the lateral direction by periodic arrays of posts placed on both sides of the guiding channel. In our recent manuscript [1], we have shown that in case of metallic (PEC) rods, a single array at both sides of the channel is usually enough to provide strong field confinement and guiding because the leakage of the guided waves is suppressed by the cutoff phenomenon between the adjacent PEC rods. However, at higher frequencies the metals become increasingly lossy and dielectric.

materials start to play an important role [2]. Furthermore, the big technological step enabled by 3-D printers allows a cheap and rapid prototyping by additive manufacturing of plastic materials has attracted an additional interest of engineers for all-dielectric waveguide structures and integration schemes. However, the phenomenon of field confinement in the guiding region in case of dielectric rods is still an open research issue as the wall's elements are completely different from that in case of PEC rods. In case of dielectric rods, the confinement is explicable by the electromagnetic band-gap behavior similar to Bragg reflection in a periodic multilayered structure along the x-axis (Fig. 1). As a result, the good confinement of the field could be achieved at the expense of a larger transversal extent of the device.

We numerically analyze the PWW composed of periodically distributed dielectric circular rods as wall elements using our originally developed formalism based on lattice sums technique [3–5].



(a) (b)

Figure 1: (a) Transversal view of a dielectric PWW, where h is a period of the structure, w is a width of the waveguide, r is a radius of the dielectric rod, p is a distance between the layers, ε is a relative dielectric permittivity of the rod and R^N stands for a generalized reflection matrix of the N-layered periodic structure. Guidance of a fundamental TE mode (Ey, Hx, Hz) injected in the dielectric PWW through Port 1 is considered. (b) Normalized phase constant $\beta_0 h/2\pi$ (blue line) and normalized attenuation constant $\alpha h/2\pi$ (red line) of the lowest-order TE mode (Ey, Hx, Hz) for a 1-layered (solid line) and 2-layered (dashed line) PWW composed of dielectric rods with: $r = 0.353\,\text{mm}$, $h = 1.96\,\text{mm}$, $p = 1.96\,\text{mm}$, $w = 3.92\,\text{mm}$, $\varepsilon = 11.56$. The frequency dependence of $\beta_0 h/2\pi$ for a multilayered $N = 100$ are also illustrated by a blue dashed-dotted line.

The latter enables us to calculate the propagation constant of complex modes (namely the phase constant and the attenuation constant) for a wide class of periodic structures and electromagnetic bandgap structures in a very short computation time as shown in Fig. 1(b). Combining our full-wave formalism and optimization algorithms, the geometrical parameters of PWW are properly tracked down to achieve a best possible confinement with a relatively small number N of PWW layers in the desired frequency range aiming at the realization of highly compact passive circuits. For the computer-guided filter design we are relying on a breeder Genetic Algorithm (GA), which has already proven to be efficient in tracking down high-quality solutions in the framework of numerical structural optimization, e.g., in dense integrated optics. The proposed optimization scheme is easily applicable to the design of PWW-based filter structure, as the forward solver [3–5] is computationally efficient. We are now working on topology optimization method to further increase the performance of the device.

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Topics to be discussed

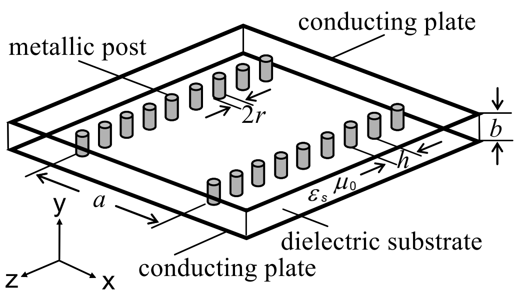
1. Formulation of the Problem.
2. Modal Analysis of Post-Wall Waveguides (PWW).
3. Optimization of PWW-based bandpass Filters using Genetic Algorithm.
4. Comparison with another optimization technique - Space-Mapping technique.
5. Optimization of PWW-based Filters using Gradient-based method.

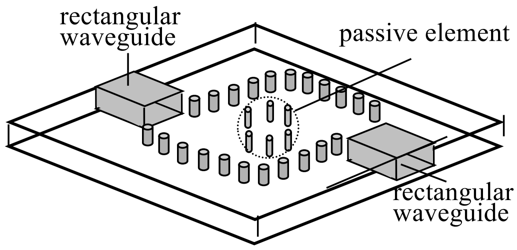
Formulation of the Problem (1)

Planar microwave (millimeter wave) circuits

- $b \ll \lambda$
- Two-dimensional $(\partial/\partial y = 0)$ model fields
- Mode fields like TE_{m0} modes in rectangular waveguide

A very good alternative of the conventional non-planar guiding devices is a *Post-Wall Waveguide* also called *Substrate Integrated Waveguide*. It can completely be integrated together with planar structures onto the same planar substrate with the same processing or fabrication techniques.





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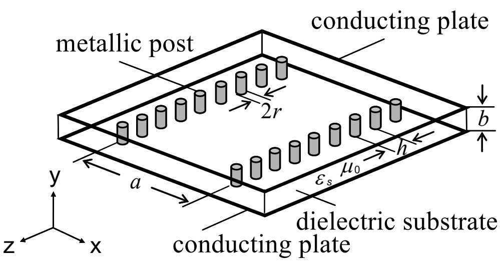
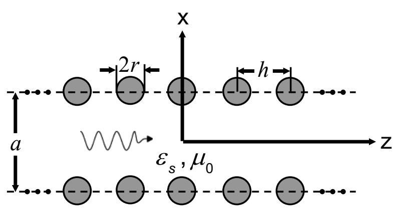
Formulation of the Problem (2)





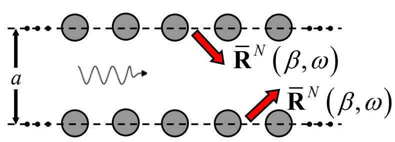
1-layer structure

Consider TE modes. If we assume a longitudinal field variation of exp($ib\,z$), the two-dimensional guided wave propagating along the guiding region |x| < a/2, is expressed as follows:

$$E_y(x,z) = \mathbf{U}^{+}(x,z)\cdot \boldsymbol{c}^{+} + \mathbf{U}^{-}(x,z)\cdot \boldsymbol{c}^{-}$$

$$\mathbf{U}^{\pm}(x,z) = \left[\exp\left[(i\kappa_\ell(x \mp a/2))\right]\exp(i\beta_\ell z)\delta_{lm}\right]$$

$$\beta_\ell = \beta + 2\ell\pi/h,\ \kappa_\ell = \sqrt{k_s^2 - \beta_\ell^2},\ \ k_s = \omega\sqrt{\varepsilon_s \mu_0}$$



β : propagation constant

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Modal Analysis of PWW (1)

Rigorous Formulation:

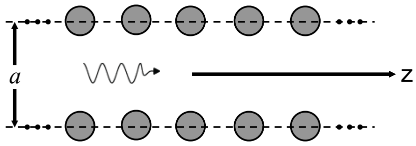
$$\det[\mathbf{I} - \mathbf{W}(\beta,\omega)\overline{\mathbf{R}}^N(\beta,\omega)] = 0 \qquad (1)$$

$$\mathbf{W}(\beta,\omega) = [\mathrm{e}^{i\kappa_\ell a}\,\delta_{lm}], \quad \kappa_l = \sqrt{k_s^2 - (\beta + 2\ell\pi/h)^2} \qquad (2)$$

$$k_s = \omega\sqrt{\varepsilon_s \mu_0}$$

$\overline{\mathbf{R}}^N(\beta,\omega)$: Generalized reflection matrix of N-layered post walls. Calculated by the full-wave modal analysis [1].

Long Wavelengths Approximation:



$$1 - \mathrm{e}^{i\kappa_0 a}\,\overline{R}_{00}^N(\beta,\omega) = 0 \qquad (3)$$

Only the fundamental Floquet mode with $\ell = 0$ is propagating and all other Floquet modes are evanescent.

[1] V. Jandieri, P. Baccarelli, G. Valerio and G. Schettini, "1-D Periodic lattice sums for complex and leaky waves in 2-D structures using higher-order Ewald formulation," *IEEE Transaction on Antennas and Propagation*, vol. 67, no. 4, 2019.

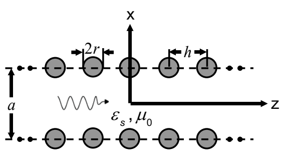
Modal Analysis of PWW (2)

Properties of $\overline{R}_{00}^N(\beta,\omega)$

$$\left|\overline{R}_{00}^N(\beta,\omega)\right| \simeq 1.0 \text{ and } \left|\overline{R}_{00}^N(\beta,\omega)\right| \le 1.0 \qquad (4)$$

$$1 - \left|\overline{R}_{00}^N(\beta,\omega)\right|^2 \Rightarrow \text{ small perturbation related to leakage}$$

Equivalent rectangular waveguide

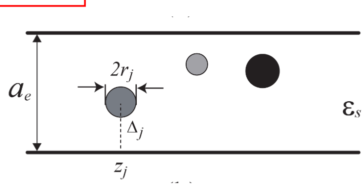


Effective width: $a_e = a + \Delta a$

$$\overline{R}_{00}^N(\beta,\omega) = -1 \Rightarrow \mathrm{e}^{-i\kappa_0(a+\Delta a)} = \mathrm{e}^{-i\kappa_0 a_e} = -1 \qquad (5)$$

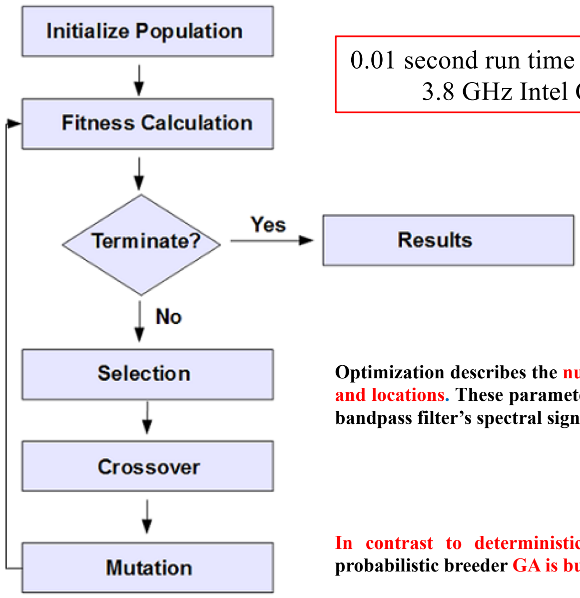
$$a_e(\omega) = \frac{\pi}{\kappa_0(\omega)} \quad \text{(for } \omega \text{ and } \beta \text{ satisfying Eq.(3))}$$

Theory of Images for S-parameters



A. Akopian, G. Burduli, V. Jandieri, H. Maeda, W. Hong, A. Omar, K. Yasumoto, D.H. Werner and D. Erni, "Analysis of Electromagnetic Scattering in Post-Wall Waveguides and Its Application to Optimization of Millimeter Wave Filters," *IEEE Open Journal on Antennas and Propagation*, Special Section on "Direct and Inverse Electromagnetic Scattering Methods," vol. 1, pp. 448-455, 2020.

Optimization of PWW-based Filters using GA (1)

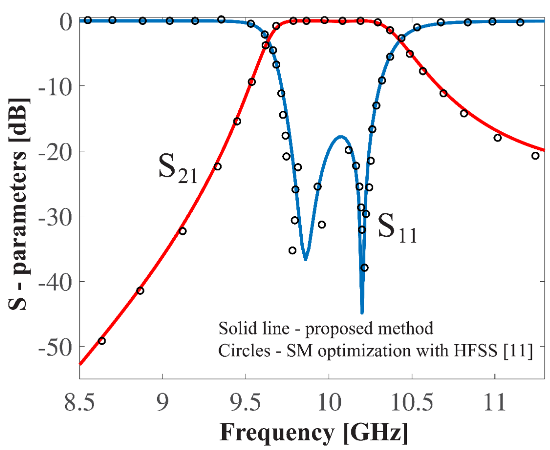


0.01 second run time per computed frequency using a 3.8 GHz Intel Core i7 with 32 GB RAM

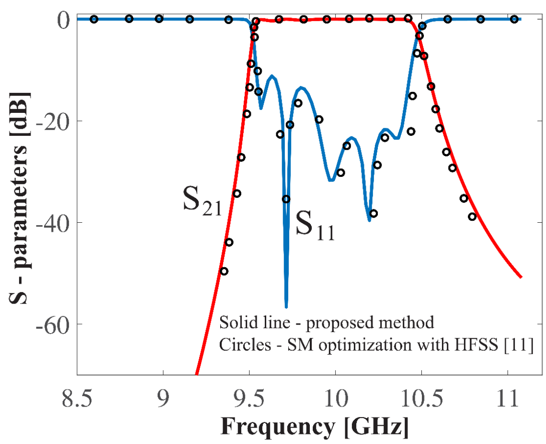
Optimization describes the number of the loaded posts, their radii, material constants and locations. These parameters make the strongest influence on the formation of the bandpass filter's spectral signature.

In contrast to deterministic optimizers, which usually need an initial starting topology, our probabilistic breeder GA is built on a randomly initialized population of potential PWW structures.

Comparison with Space-Mapping technique



S-parameters of 3-pole filters with iris windows calculated using our proposed method (solid line) and the SM optimization technique in conjunction with the mono-modal equivalent circuit model and Ansoft HFSS simulations (circles) [1].



S-parameters of 8-pole filters with iris windows calculated using our proposed method (solid line) and the SM optimization technique in conjunction with the mono-modal equivalent circuit model and Ansoft HFSS simulations (circles) [1].

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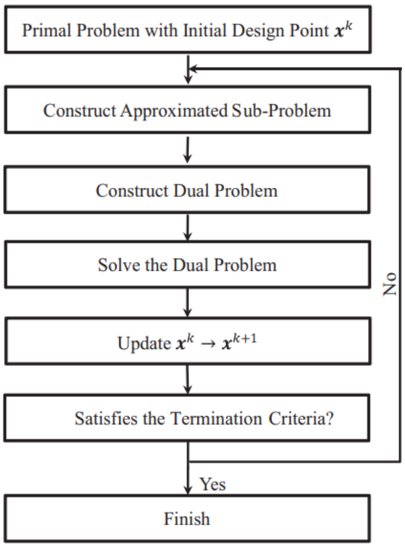
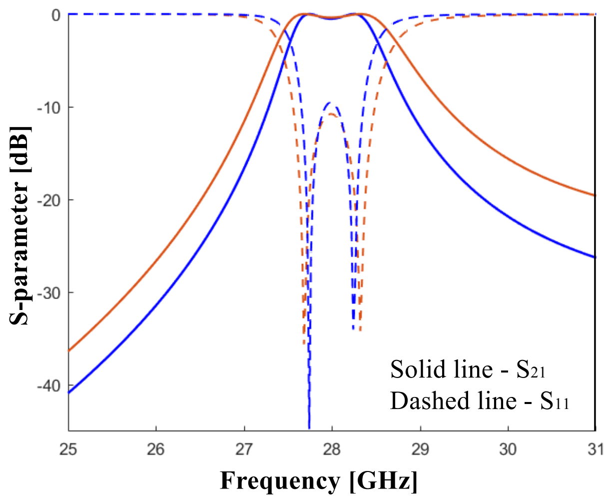
Optimization of PWW-based Filters using MMA





S-parameters of 3-pole filters optimized by GA (orange lines) and MMA (blue lines) techniques. GA used about 800 evaluations, whilst MMA used less than 200

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Thank You!