Array of folded patches

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Tchebyshev array factor design

The design parameters for the array are:

Parameter	Value
# elements	$2N+1=5$
Mean lobe/side lobe ratio	$R=120 \cong 41.58\,dB$
Frequency	$f\ =2.1\,GHz$

It's been specifically required to find the optimal inter-element spacing so that the minimum of the beamwidth will be reached:

$$d_{opt} \rightsquigarrow \min\{BW_{fn}\}$$

$$d_{opt}=\lambda\left[1-\frac{\arccos\left(\frac{1}{\gamma}\right)}{\pi}\right] \tag{1}$$

$$\gamma=\cosh\left[\frac{1}{2N}\ln\left(R+\sqrt{R^2-1}\right)\right]$$

where $\lambda=\frac{c}{f}$ is the frequency in the free-space . In this case, $d_{opt}\in\left(\frac{\lambda}{2},\lambda\right]$, which means that The coefficients a and b related to the Tchebyshev polynomial approximation for the array will be chosen by following the $d_{opt}\in\left(\frac{\lambda}{2},\lambda\right]$ condition:

$$T_2\left[x=a+b\cos u\right]=C_0+2C_1\cos u+C_2\cos 2u=(2a^2+b^2-1)+4ab\cos u+b^2\cos 2u \tag{2}$$

Once the amplitude current feed coefficients are computed (C_n, $n=\overline{0,2}$), the tapering efficiency can be calculated:

$$\eta_T=\frac{1}{2N+1}\frac{||C_0+2C_1+2_2||^2}{C_0^2+2C_1^2+2C_2^2} \tag{3}$$

Let's consider two cases of uniform spacing array and:

$$\text{Uniform Amplitude (UA)} \quad || \quad \text{Non-uniform Amplitude (NUA, Tchebyshev)} \tag{4}$$

The comparison will show how

$$BW_{fn}^{[UA]}<BW_{fn}^{[NUA]}$$

$$BW_{fn}^{[NUA]}=2\frac{180}{\pi}\left[\frac{\pi}{2}-\arccos\left(\frac{\arccos\left(\frac{\cos\left(\frac{\pi}{2N}-a\right)}{b}\right)}{k_0 d}\right)\right] \tag{5}$$

$$BW_{fn}^{[UA]}=\frac{2\lambda}{N\,d}\frac{180}{\pi}$$

Parameter	Value
Feed coefficients $[A]$	C_0 || $C_1 = C_{-1}$ || $C_2 = C_{-2}$ 41.2 || 29.8 || 9.6
Normalized feed coefficients to $C_{\max}$	C_0^* || $C_1^* = C_{-1}^*$ || $C_2^* = C_{-2}^*$ 1.000 || 0.7215 || 0.2336
Tapering efficiency	$\eta_T = 79\,\%$
Beamwidth	Tchebyshev || Uniform $50.6°$ || $34.8°$

Now, discussing the results is mandatory:

Max/min feed ratio Even if this is the design of a Non-Uniform Amplitude Array, the less the ratio $r_{\max/\min} = \frac{C_{\max}}{C_{\min}}$ is, the more efficient distribution of current is reached. In this particular design:

$$r_{\max/\min} \cong 4.39 \tag{6}$$

meaning that if a damage of the element with the $C_{\max}$ level of feed occurs, most part of the efficiency will be lost. In any case, the tapering efficiency shows how it will not be possible to take advantage of $21\,\%$ of the array in an ideal situation, remembering that this design model can be discerned by the real circumstance in terms of the Tchebyshev error [Balanis].

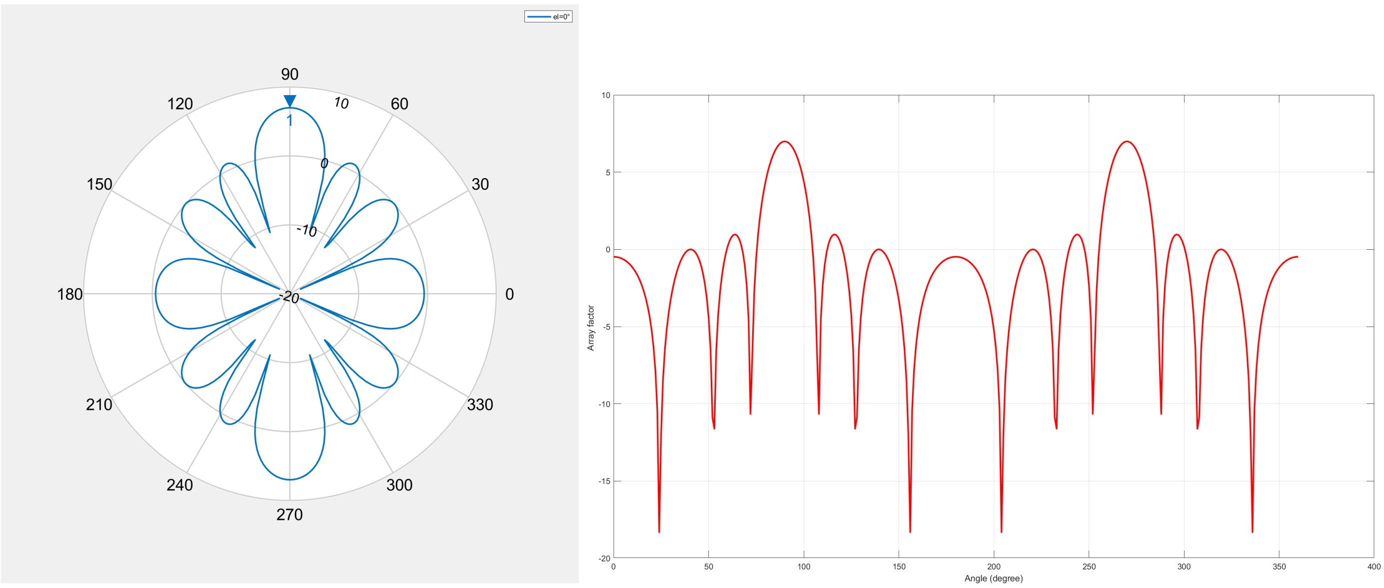

Figure 1: Array factor polar (left) and rectangular (right) diagrams

Rectangular folded patch design

The design requirements are listed below:

Mesh density refinement

A FR4 substrate thickness of $h_{sub} = 0.8\,mm$ has been selected so it could be considered as a thin one:

$$\lambda_{sub} = 0.0652\,m \quad \rightsquigarrow \quad \frac{h_{sub}}{\lambda_{sub}} \cong \frac{1}{81}$$

Folded patch design parameters	
Parameter/Component	**Value/Type/Material**
Frequency	$2.1\,GHz$
Substrate	FR4
Relative permittivity Relative permeability Loss tangent Thickness	$\varepsilon_{FR4} = 4.8$ $\mu_{FR4} \cong 1$ $\{\tan(\delta)\}_{FR4} = 0.0260$ $h_{FR4} = 0.8\,mm$
Patch (pre-optimized features)	Copper
Conductivity Thickness Length Width	$\kappa_{copper} = 5.96{\cdot}10^{7}\,S/m$ $h_{patch} = 3.556 \cdot 10^{-5}\,m$ $L_{patch} \cong \frac{\lambda_{FR4}}{4} = 0.0171\,m$ $W_{patch} \cong 0.419\,m$
Ground	Copper (same conductivity listed above)
Thickness Length Width	$h_{GND} = h_{patch}$ $L_{GND} = 0.04\,m$ $W_{GND} = 0.06\,m$
Feed	Coaxial cable

In case of thin substrates ($h/\lambda \leq 1/50$), the Antenna Toolbox suggests to mesh the antenna using dielectric in auto mode. The other two available substrate thicknesses ($1.0\,mm$ and $1.6\,mm$) have not been adopted because the Antenna Toolbox reference doesn't give any information about accuracy of the results in case of $h_{sub} \in \left(\frac{\lambda}{50}, \frac{\lambda}{10}\right)$.

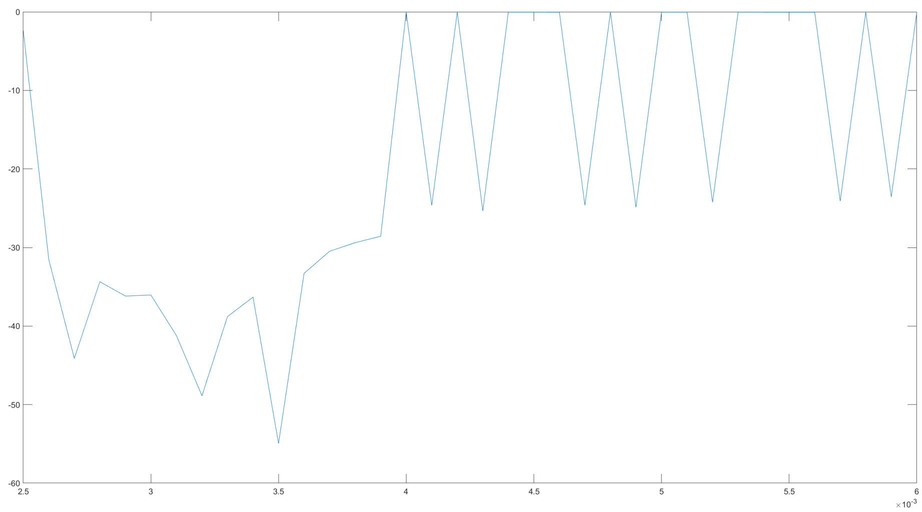

Figure 2: Minimum of the reflection coefficient $\Gamma\,[dB]$ in the frequency range $2.0 \div 2.2\,GHz$ depending on the varying mesh density level

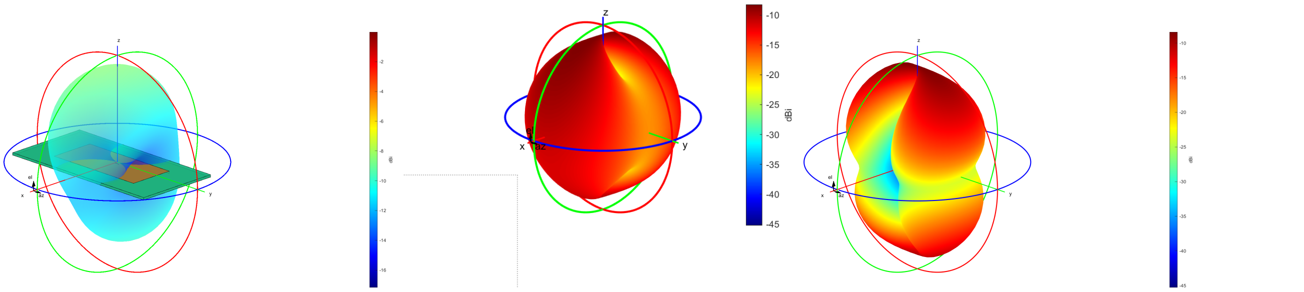

Figure 3: Gain pattern (left), gain pattern with vertical polarization (center) and with the horizontal one (right)

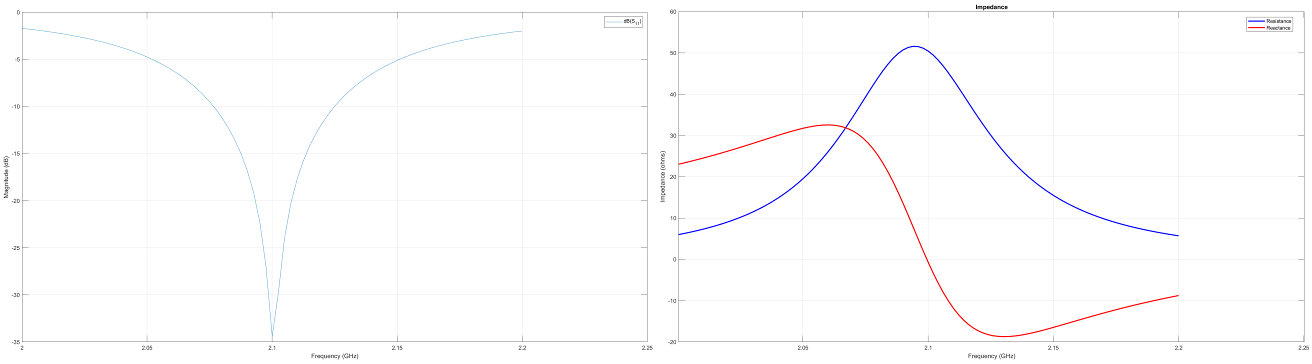

Figure 4: Reflection coefficient (left) and impedances (right) plots depending on $f \in 2.0 \div 2.1\, GHz$

Patch parameters

$$\begin{aligned} L + W - w_{SC} &= \frac{\lambda}{4} + h_{sub} \\ W &= \frac{\lambda_0}{2} \sqrt{\frac{2}{\varepsilon_r + 1}} \end{aligned} \tag{7}$$

$$\begin{aligned} BW_E &= 2 \arccos \sqrt{\frac{7.03\, \lambda_0^2}{4\,(3\, L_e^2 + h^2)\, \pi^2}} \\ BW_H &= 2 \arccos \sqrt{\frac{1}{2 + k_0\, W}} \end{aligned} \tag{8}$$

$$\ell_{feed} = \frac{L}{\pi} \arccos \sqrt{\frac{R_{in}}{R_r}} \tag{9}$$

Overall array performance evaluation