# Interaction model

$$p_i(\omega) = \alpha(\omega)\left[E_0(\omega) + g_{\mathrm{EPR}}(\omega)\, p_i(\omega) + \sum_j g_{ij}(\omega)\, p_j(\omega)\right],$$

$$g_{\mathrm{EPR}}(\omega) = \frac{\boxed{-\mu_0 \int_V \mathrm{d}\vec{r}^{\,3}\ \vec{\mathcal{P}}^*(\vec{r},\omega)\cdot \int_V \mathrm{d}\vec{r}^{\,\prime 3}\ \overleftrightarrow{G}^H(\vec{r},\vec{r}^{\,\prime},\omega)}\,\boxed{\overleftrightarrow{\chi}_{\mathrm{m}} \int_V \mathrm{d}\vec{r}^{\,\prime\prime 3}\ \overleftrightarrow{G}^H(\vec{r}^{\,\prime},\vec{r}^{\,\prime\prime},\omega)\vec{\mathcal{P}}(\vec{r}^{\,\prime\prime},\omega)}}{\int_V \mathrm{d}\vec{r}^{\,3}\ \vec{\mathcal{P}}^*(\vec{r},\omega)\cdot\vec{\mathcal{E}}_0(\vec{r},\omega)}$$

back-action of the magnetization current on the antenna

antenna induces magnetization current in the EPR material

$$\Downarrow$$

antenna array can be effectively perceived as an anisotropic reflective layer

$$\overleftrightarrow{R}_{\mathrm{sample}} = \begin{pmatrix} r_x & 0 \\ 0 & r_y \end{pmatrix} = \begin{pmatrix} \boxed{r_{\mathrm{sub}}} + \boxed{r_{\mathrm{ant}}} & 0 \\ 0 & r_{\mathrm{sub}} \end{pmatrix}$$

reflection coefficient of a bare substrate on top of a gold mirror

radiation emitted by the antennas (polarization along the long axis)

# Gyromagnetic materials

$$\overleftrightarrow{\mu} = \begin{pmatrix} 1+\chi(\omega) & \mp \mathrm{i}\chi(\omega) & 0 \\ \pm \mathrm{i}\chi(\omega) & 1+\chi(\omega) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

anizotropic magnetic susceptibility leads to different refractive indices for the left-handed and right-handed circular polarization

$$\Downarrow$$

Faraday effect = rotation of the polarization

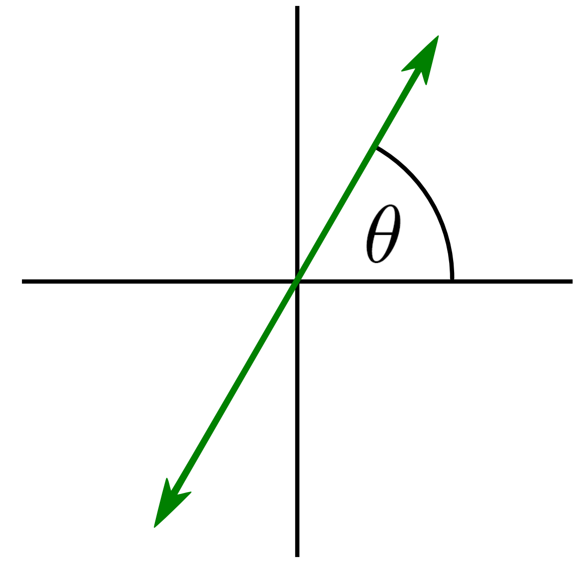
$$\overleftrightarrow{M}^{\circlearrowleft} = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ \mathrm{i} & -\mathrm{i} \end{pmatrix}\begin{pmatrix} e^{\mathrm{i}\alpha} & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & -\mathrm{i} \\ 1 & \mathrm{i} \end{pmatrix} = e^{\mathrm{i}\frac{\alpha}{2}}\begin{pmatrix} \cos\frac{\alpha}{2} & \sin\frac{\alpha}{2} \\ -\sin\frac{\alpha}{2} & \cos\frac{\alpha}{2} \end{pmatrix}$$

$$\alpha \approx \frac{2\pi}{\lambda}\chi(\omega)d$$

# Experimental setup

Polarizer

$$\overleftrightarrow{P}(\theta) = \begin{pmatrix} \cos^2\theta & \sin\theta\cos\theta \\ \sin\theta\cos\theta & \sin^2\theta \end{pmatrix}$$




$\Downarrow$

EPR material = Faraday rotator $\overleftrightarrow{M}^{\circlearrowleft}$

$\Downarrow$

Anisotropic reflection
from the substrate and antennas $\overleftrightarrow{R}_{\text{sample}}$

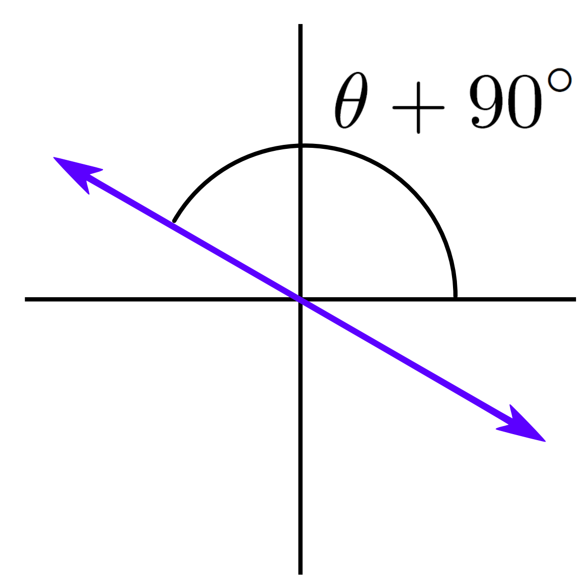
$\Downarrow$

EPR material = Faraday rotator $\overleftrightarrow{M}^{\circlearrowleft}$

$\Downarrow$

Analyzer

$$\overleftrightarrow{A}(\theta) = \overleftrightarrow{P}(\theta + 90^\circ) = \begin{pmatrix} \sin^2\theta & -\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \cos^2\theta \end{pmatrix}$$




$\Nearrow$

Demodulation

## Scenario without antennas = bare substrate

$$\vec{E}_{\text{out}} = \overleftrightarrow{A}(\theta)\, \overleftrightarrow{M}^{\circlearrowleft}(\Omega) \begin{pmatrix} r_{\text{sub}} & 0 \\ 0 & r_{\text{sub}} \end{pmatrix} \overleftrightarrow{M}^{\circlearrowleft}(\Omega) \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}$$

$$\boxed{I_{\text{out}}(\Omega) = |r_{\text{sub}}|^2\, |\sin\alpha(\Omega)|^2\, e^{-\alpha''(\Omega)}}$$

no angular dependence

## Scenario with antennas

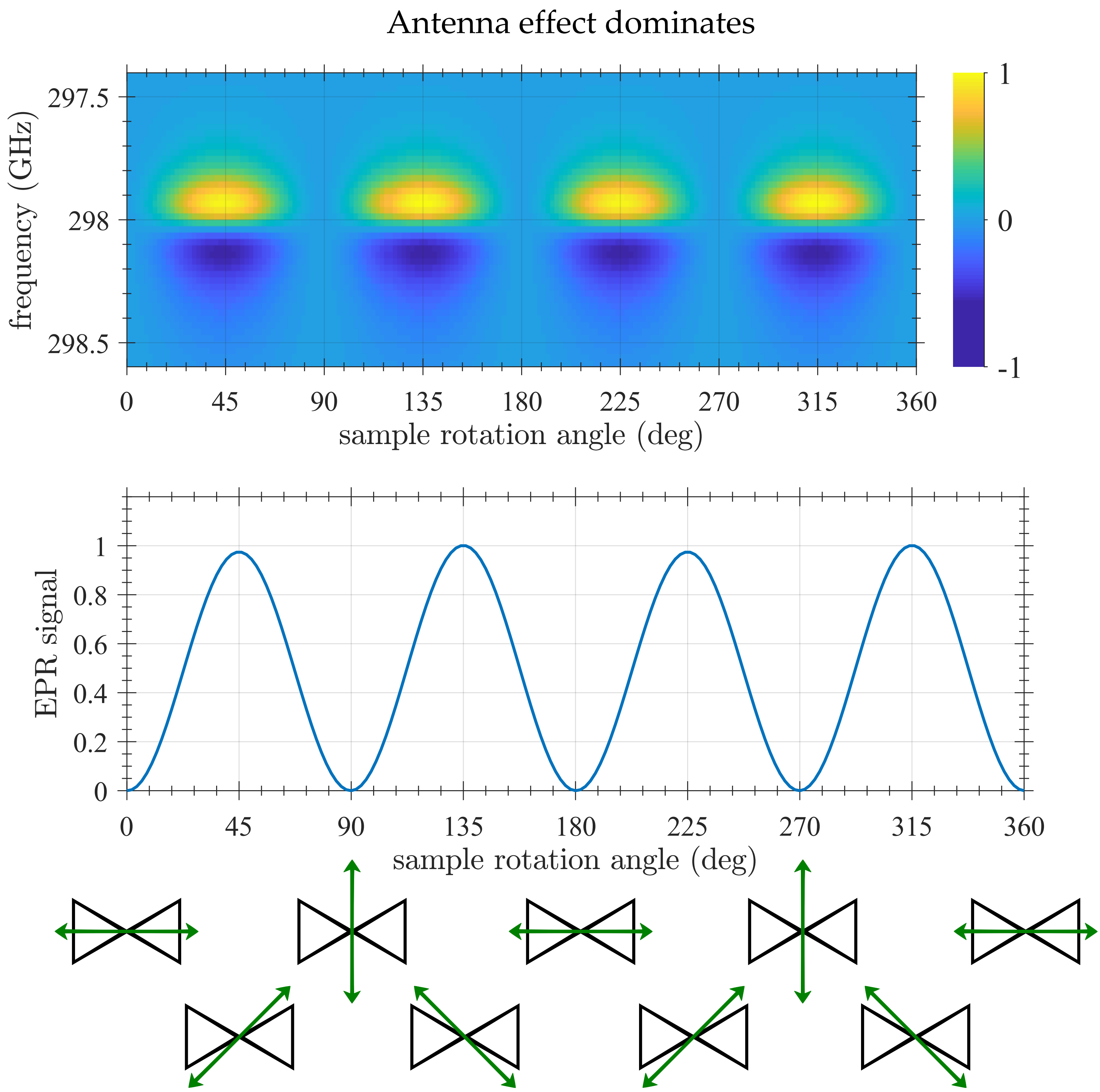
$$\vec{E}_{\text{out}} = \overleftrightarrow{A}(\theta)\, \overleftrightarrow{M}^{\circlearrowleft}(\Omega) \begin{pmatrix} r_{\text{sub}} + r_{\text{ant}} + \Delta(\Omega) & 0 \\ 0 & r_{\text{sub}} \end{pmatrix} \overleftrightarrow{M}^{\circlearrowleft}(\Omega) \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}$$

$$I_{\text{out}}(\Omega) = \boxed{\frac{1}{4}\,|r_{\text{ant}}|^2 \left(e^{-\alpha''(\Omega)} - 1\right) \sin^2 2\theta + \frac{1}{2}\text{Re}\{r^*_{\text{ant}}\Delta(\Omega)\} \sin^2 2\theta +}$$

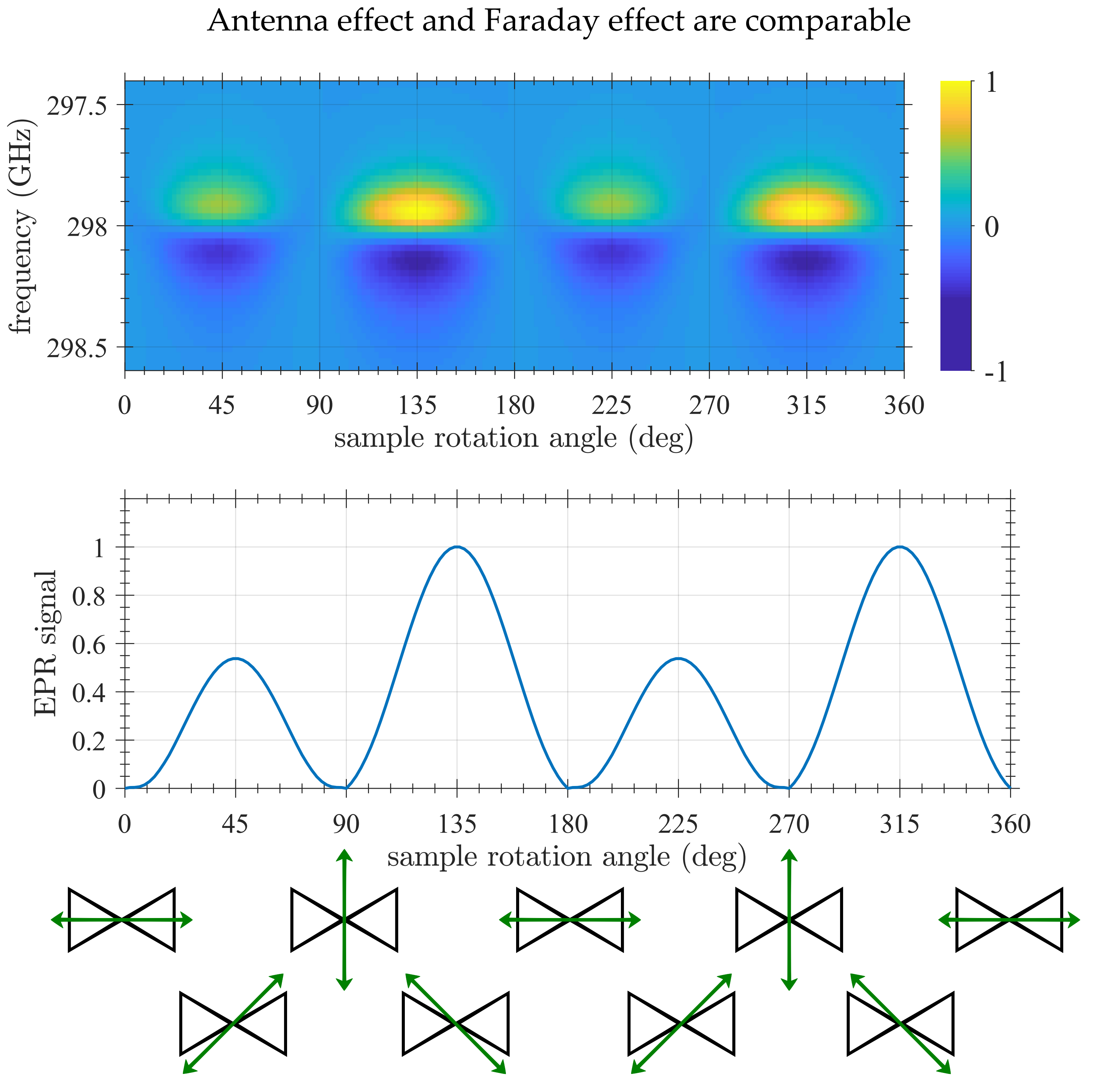
$$\boxed{+\left(\text{Re}\{r_{\text{sub}} r^*_{\text{ant}}\} + \frac{|r_{\text{ant}}|^2}{2}\right) \sin 2\theta\ \sin\alpha(\Omega)}$$

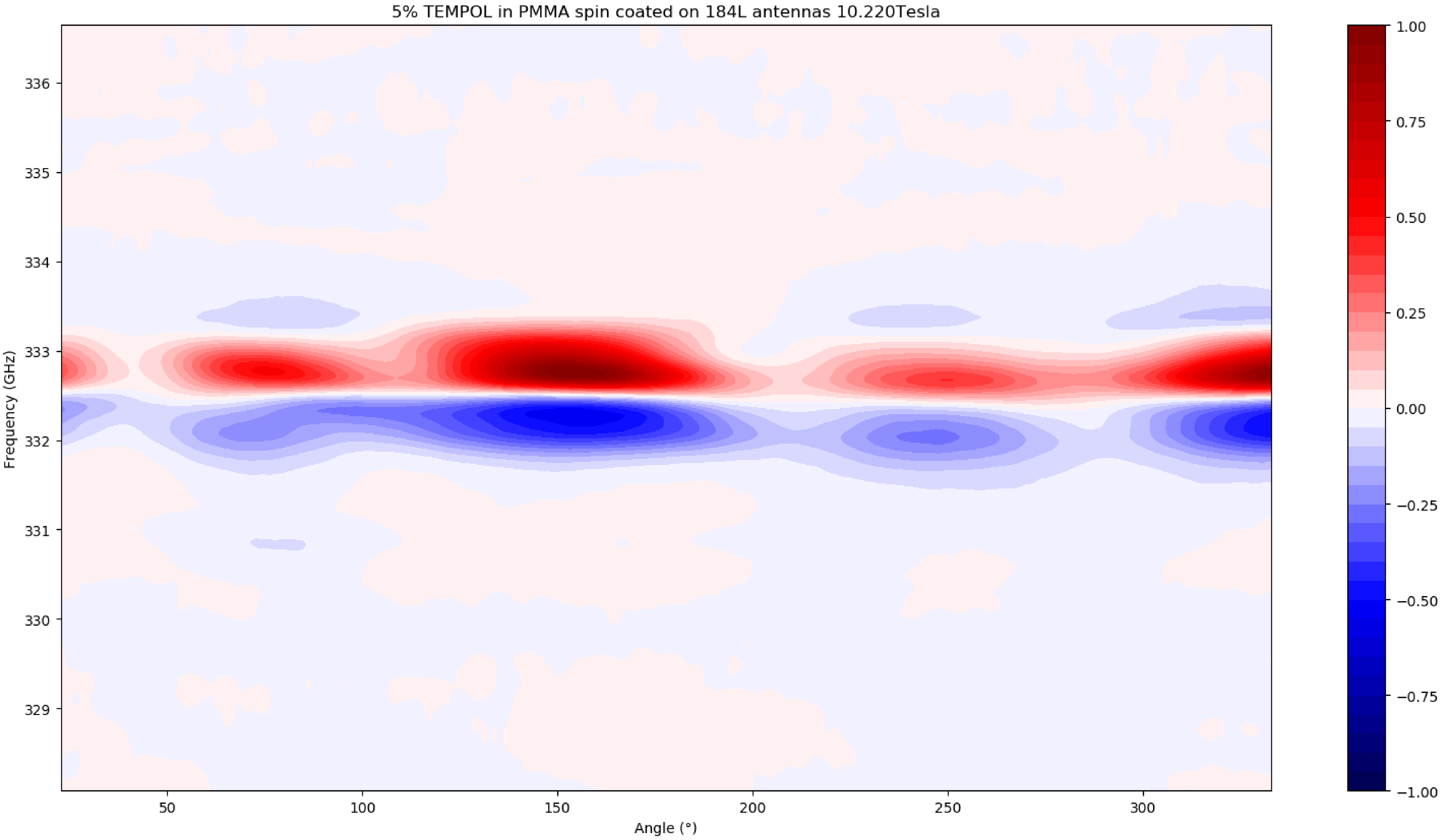
90° periodicity

180° periodicity

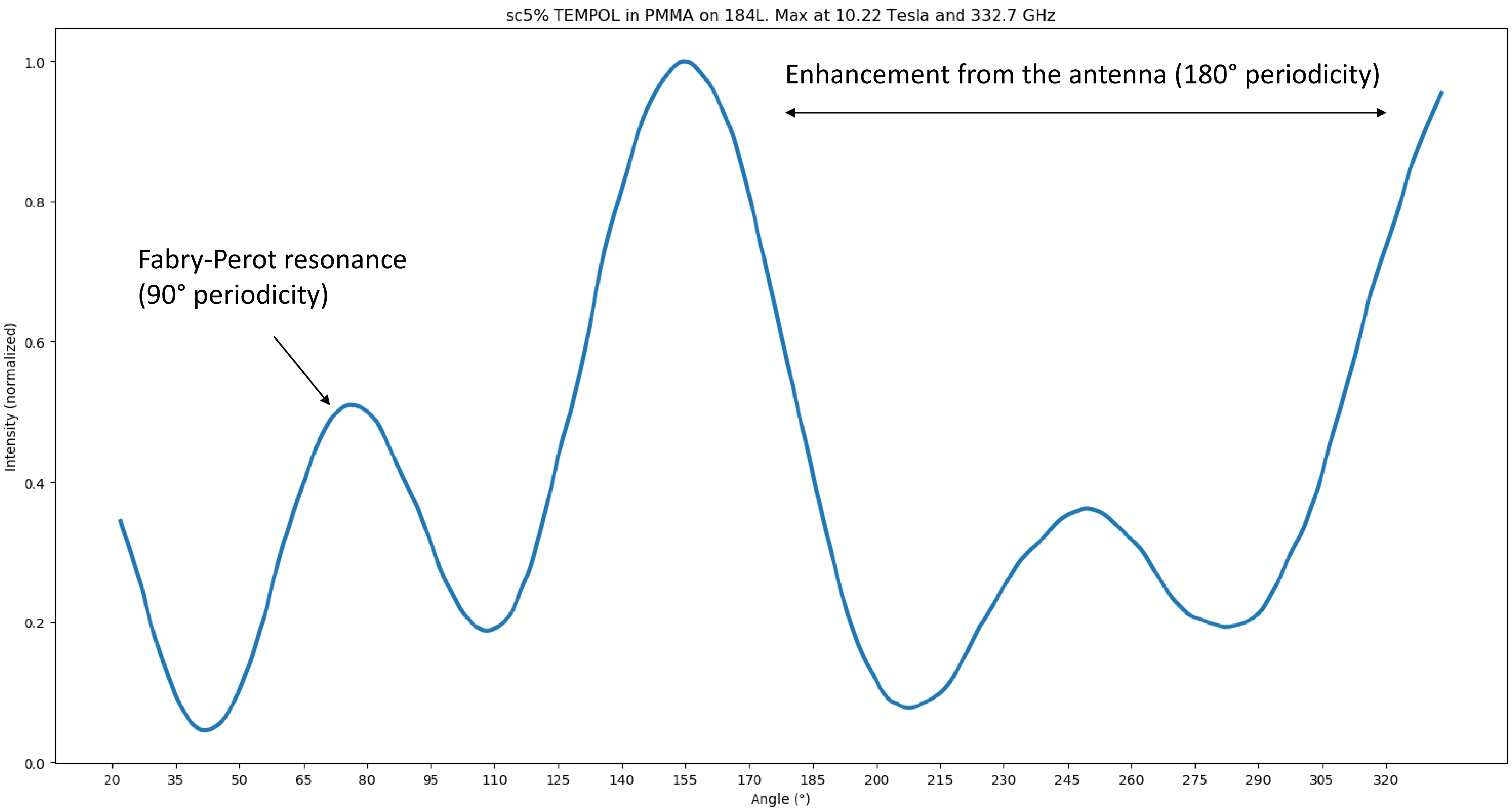


Antenna effect dominates
frequency (GHz)
297.5
298
298.5
1
0
-1
0
45
90
135
180
225
270
315
360
sample rotation angle (deg)
EPR signal
0
0.2
0.4
0.6
0.8
1
0
45
90
135
180
225
270
315
360
sample rotation angle (deg)


Antenna effect and Faraday effect are comparable
frequency (GHz)
297.5
298
298.5
1
0
-1
0
45
90
135
180
225
270
315
360
sample rotation angle (deg)
EPR signal
1
0.8
0.6
0.4
0.2
0
0
45
90
135
180
225
270
315
360
sample rotation angle (deg)



5% TEMPOL in PMMA spin coated on 184L antennas 10.220Tesla
Frequency (GHz)
336
335
334
333
332
331
330
329
Angle (°)
50
100
150
200
250
300
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00


sc5% TEMPOL in PMMA on 184L. Max at 10.22 Tesla and 332.7 GHz
Enhancement from the antenna (180° periodicity)
Fabry-Perot resonance
(90° periodicity)
Intensity (normalized)
1.0
0.8
0.6
0.4
0.2
0.0
20
35
50
65
80
95
110
125
140
155
170
185
200
215
230
245
260
275
290
305
320
Angle (°)