SAND2019-0688PE

U-slot Patch Antenna Theory and Design

PRESENTED BY

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Outline

Review patch antennas

The U-slot patch antenna historically

Intro CMT & CMA

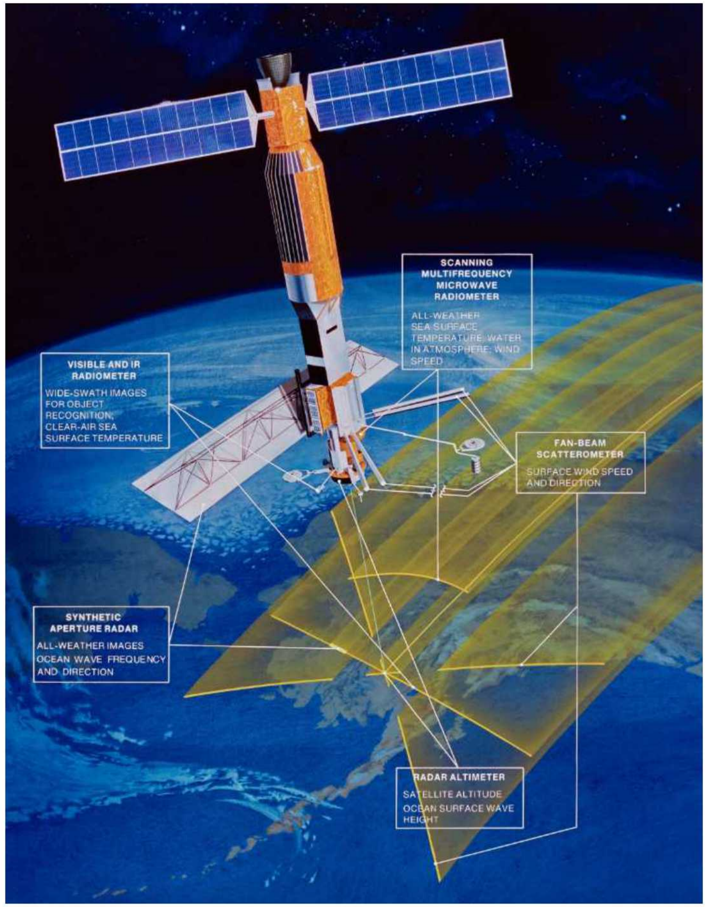
CMA of the U-slot patch > show CMT is relevant

Design methodology

Patch antennas

Attributed to Deschamps in the 50's…

Byron, Howell, Munson developed in the 70's…



A COMMEMORATION OF DESCHAMPS' AND SICHAK'S "MICROSTRIP MICROWAVE ANTENNAS": 50 YEARS OF DEVELOPMENT, DIVERGENCE, AND NEW DIRECTIONS

J. T. Bernhard[1], P. E. Mayes[1], D. Schaubert[2], and R. J. Mailloux[3]
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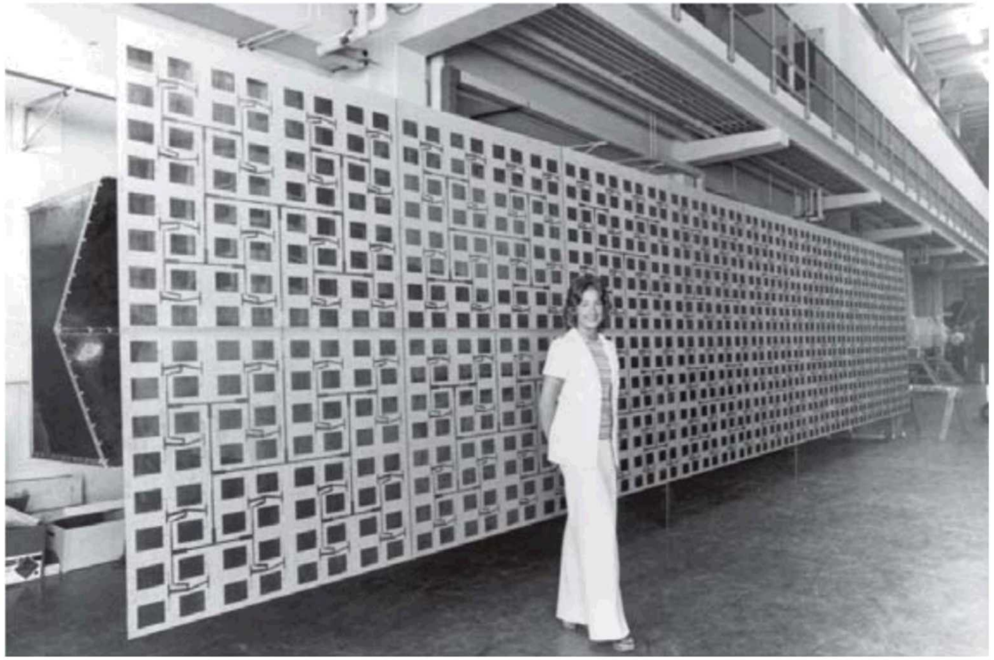
[3]Air Force Research Laboratory, Sensors Directorate 80 Scott Drive, Hanscom AFB, MA, 01731



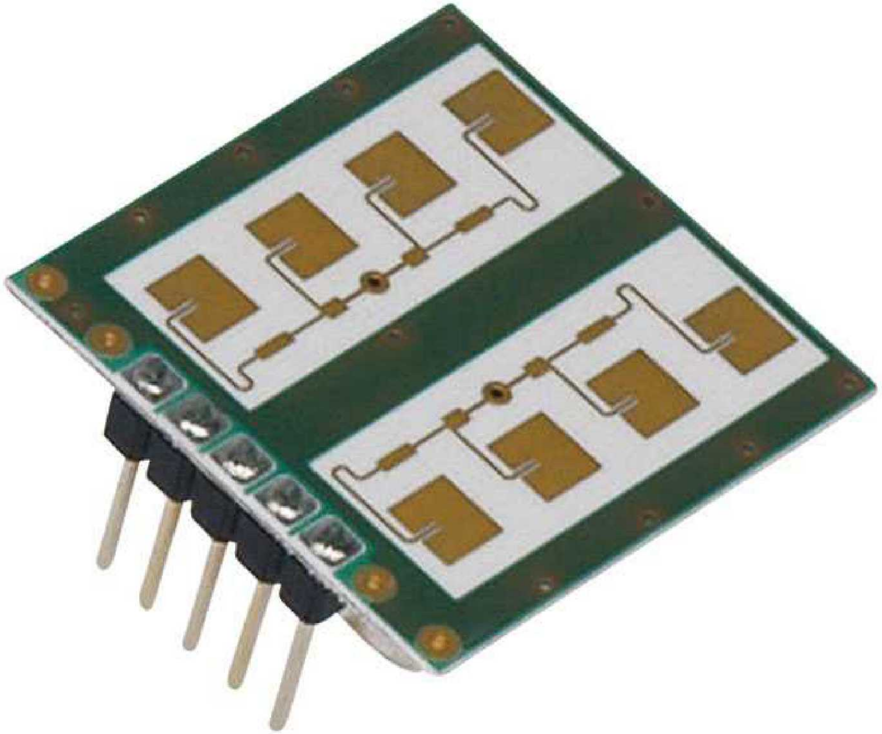
Patch antennas

Pros: Low profile, robust, can potentially be integrated w/ RF/microwave circuitry at low cost

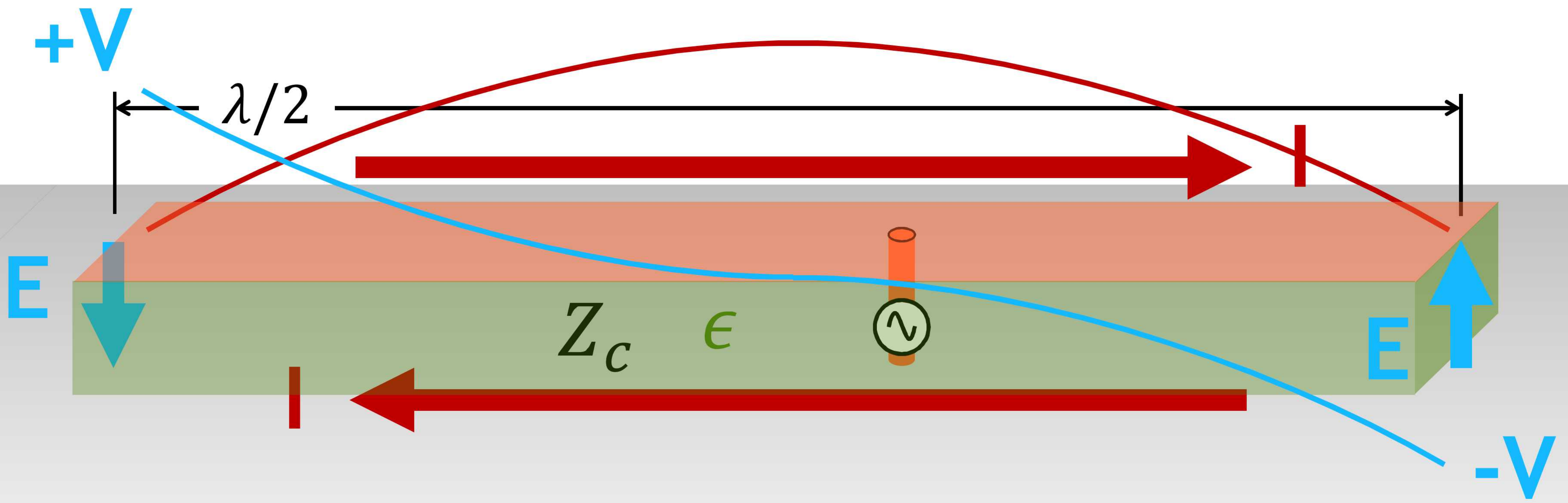
Cons: Limited power handling, narrow impedance bandwidth

Thicker patch: lower radiation Q (good!) => wider bandwidth, higher radiation efficiency

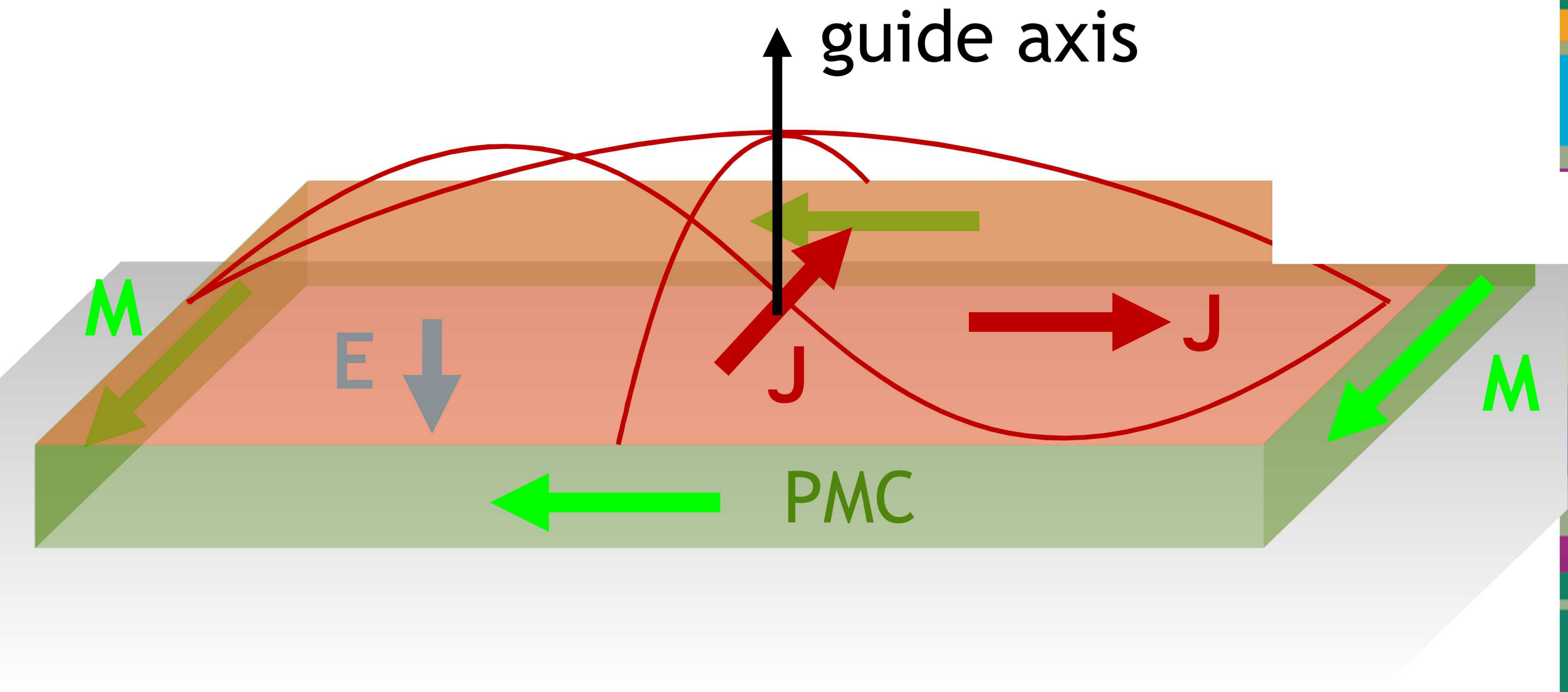
Larger substrate Dk: physically/electrically smaller patch => higher radiation Q (bad!)



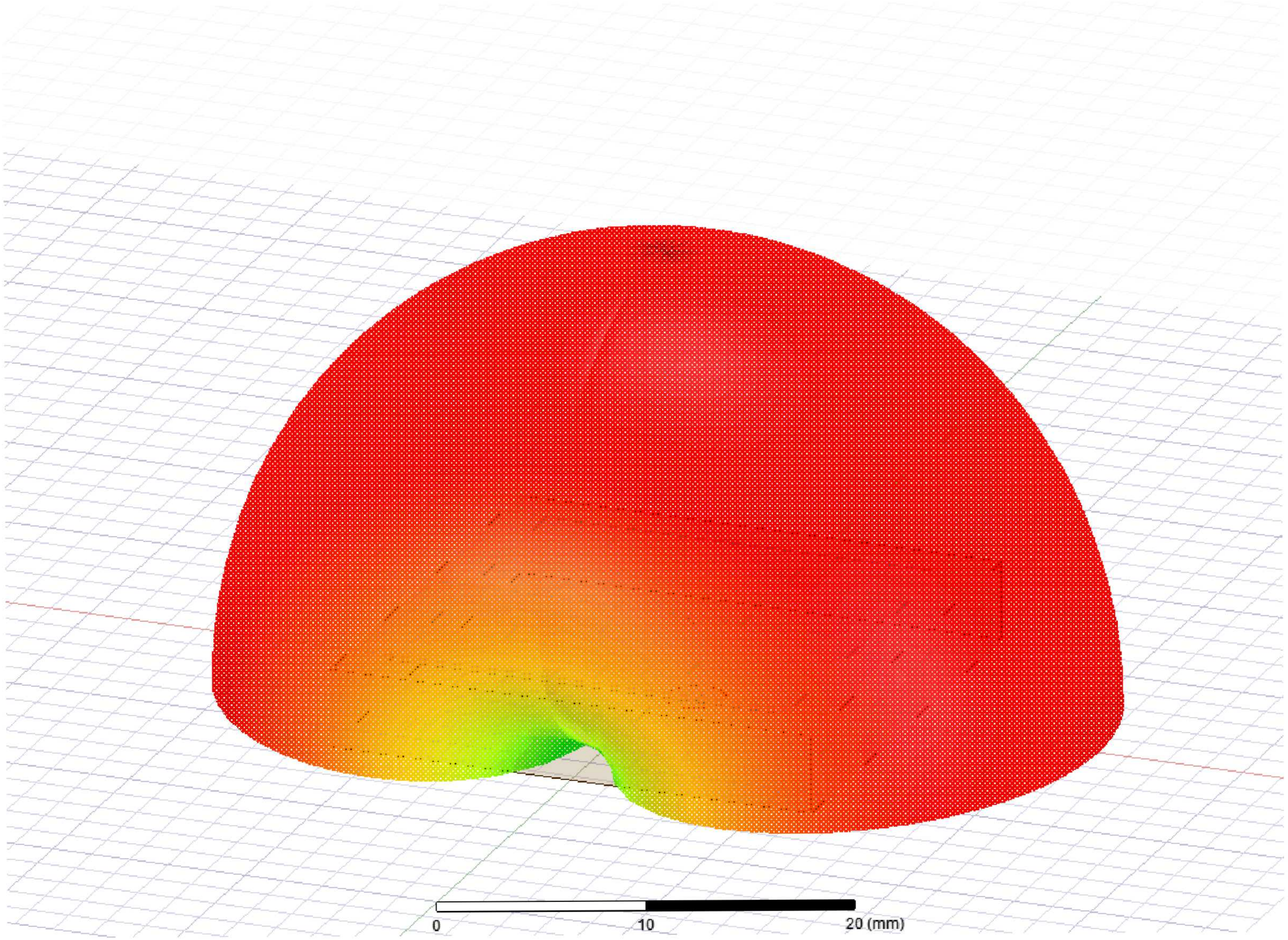
Patch antennas: t-line model



Patch antennas: cavity model

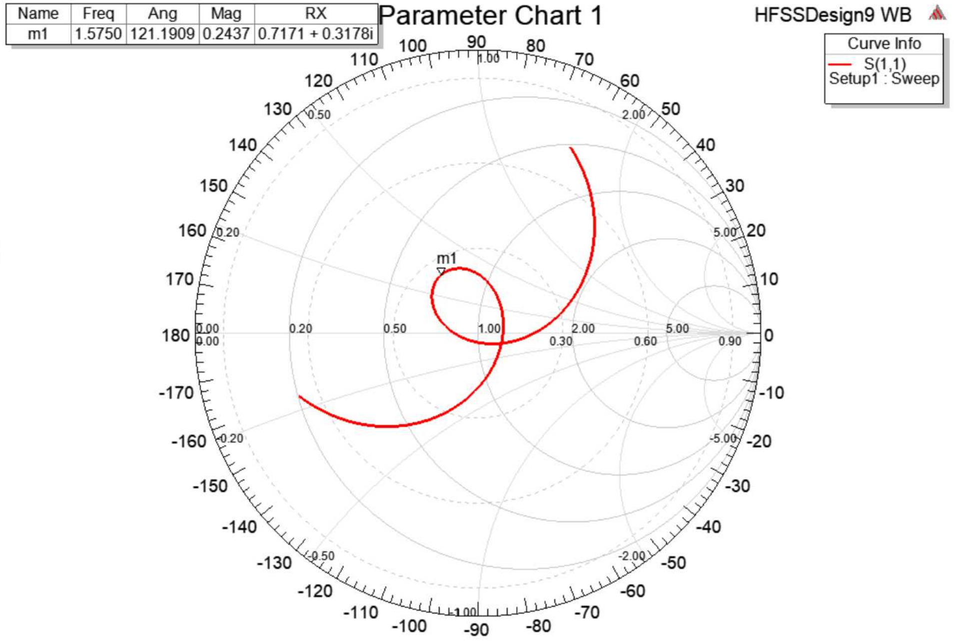


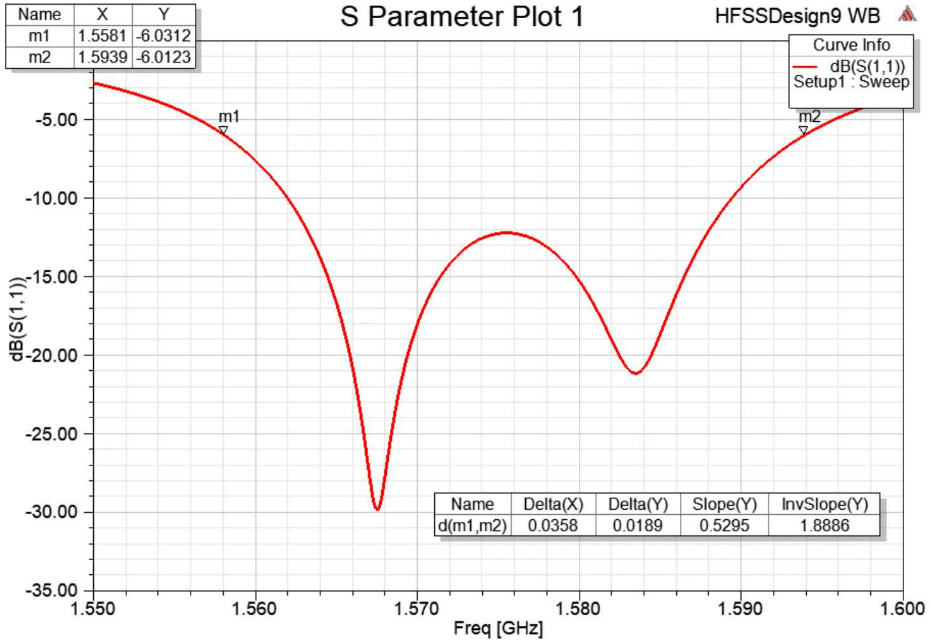
Patch antenna currents/fields example

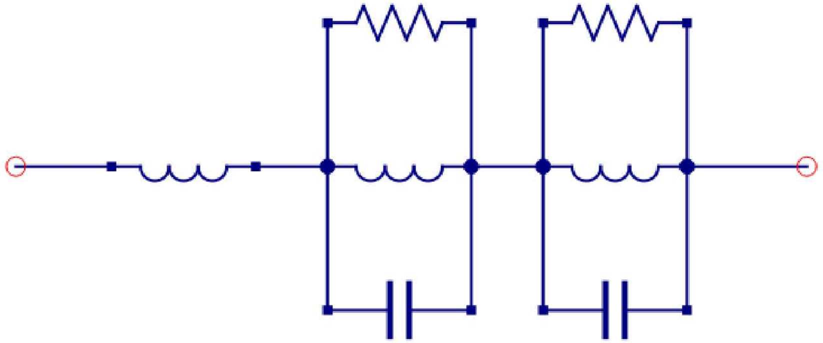


Patch antenna: impedance bandwidth and multi-moding

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$







$$Y \sim G(1 + j2Q\,\Delta\omega/\omega_0)$$

Multi-mode patches

Stacked patches

Coplanar parasitic patches

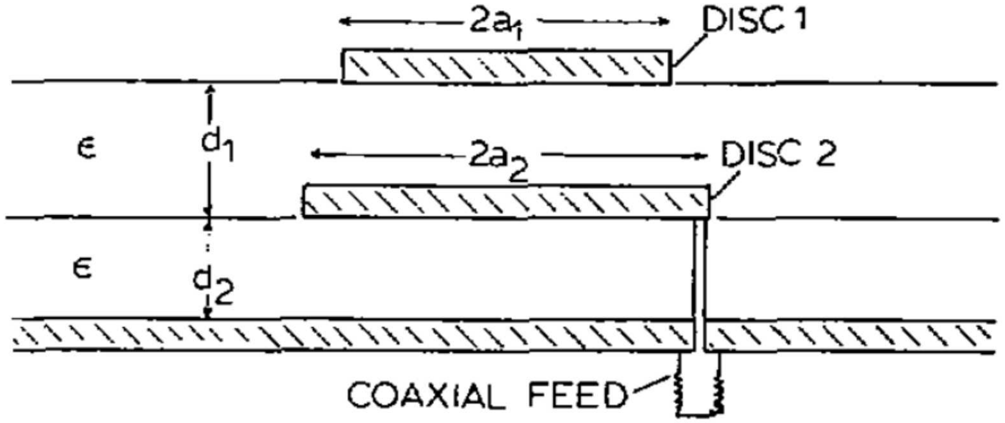
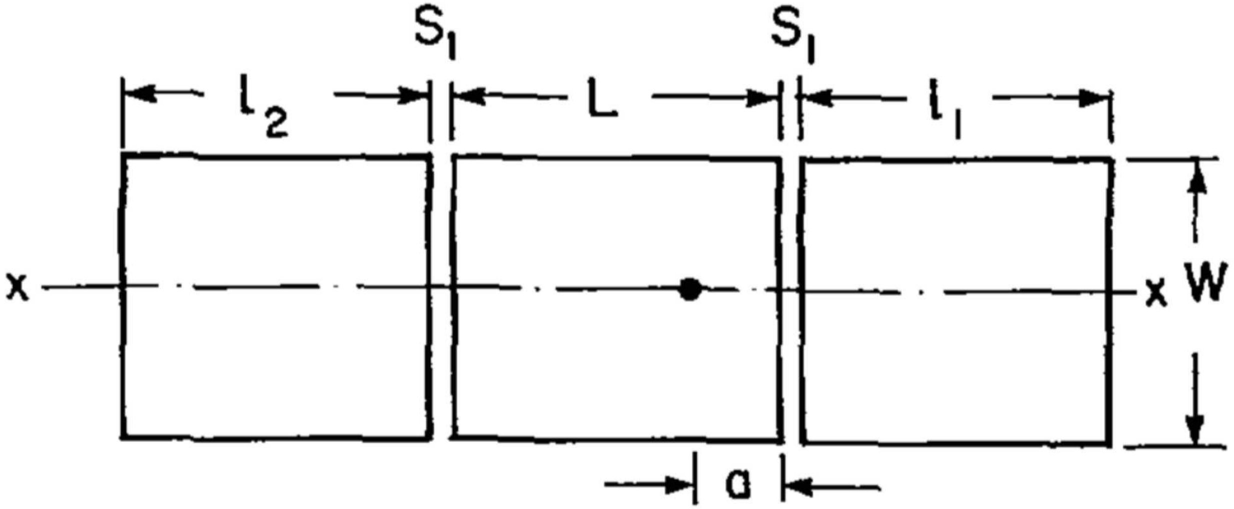


Fig. 1. Stacked circular-disc antenna structure.



(a)

S. Long and M. Walton, "A dual-frequency stacked circular-disc antenna," in IEEE Transactions on Antennas and Propagation, vol. 27, no. 2, March 1979.
G. Kumar and K. Gupta, "Broad-band microstrip antennas using additional resonators gap-coupled to the radiating edges," in IEEE TAP, vol. 32, no. 12, Dec 1984.

U-slot patches historically

Huynh and Lee, 1995

BW about 30%

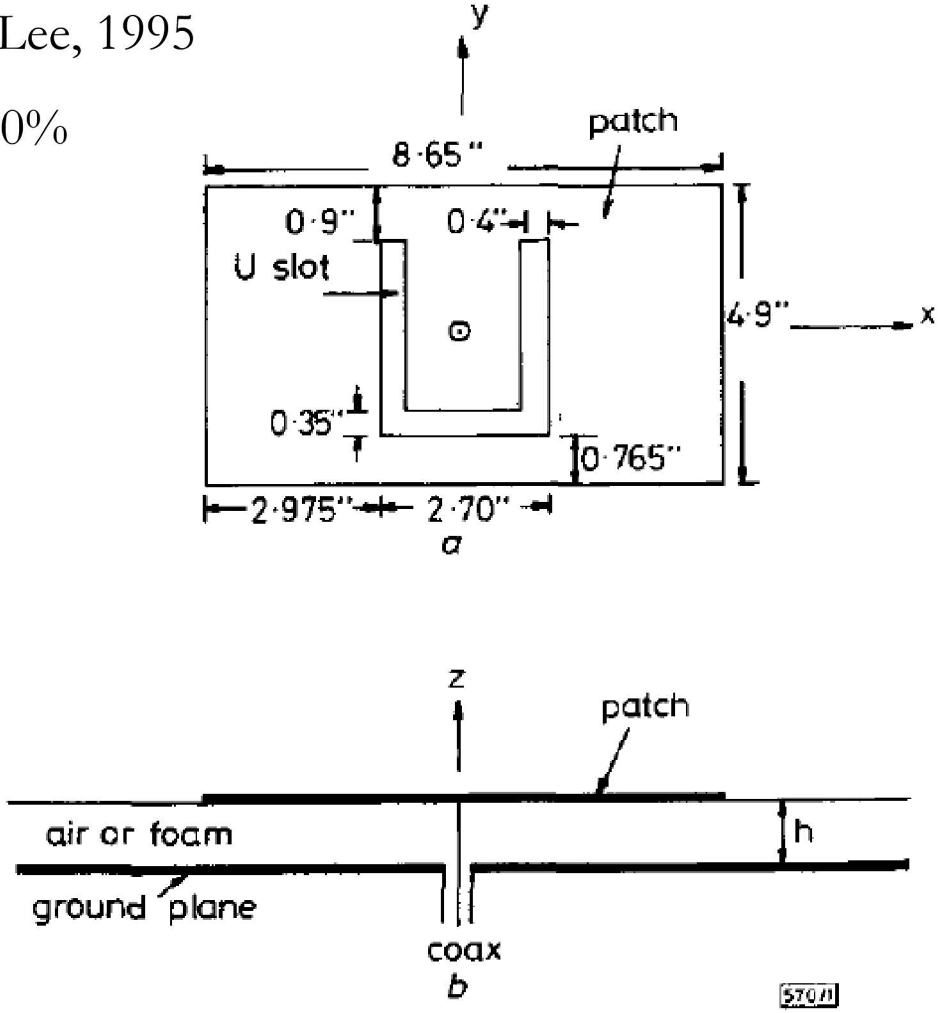


Fig. 1 *Geometry of coaxially-fed rectangular patch with U shaped slot*

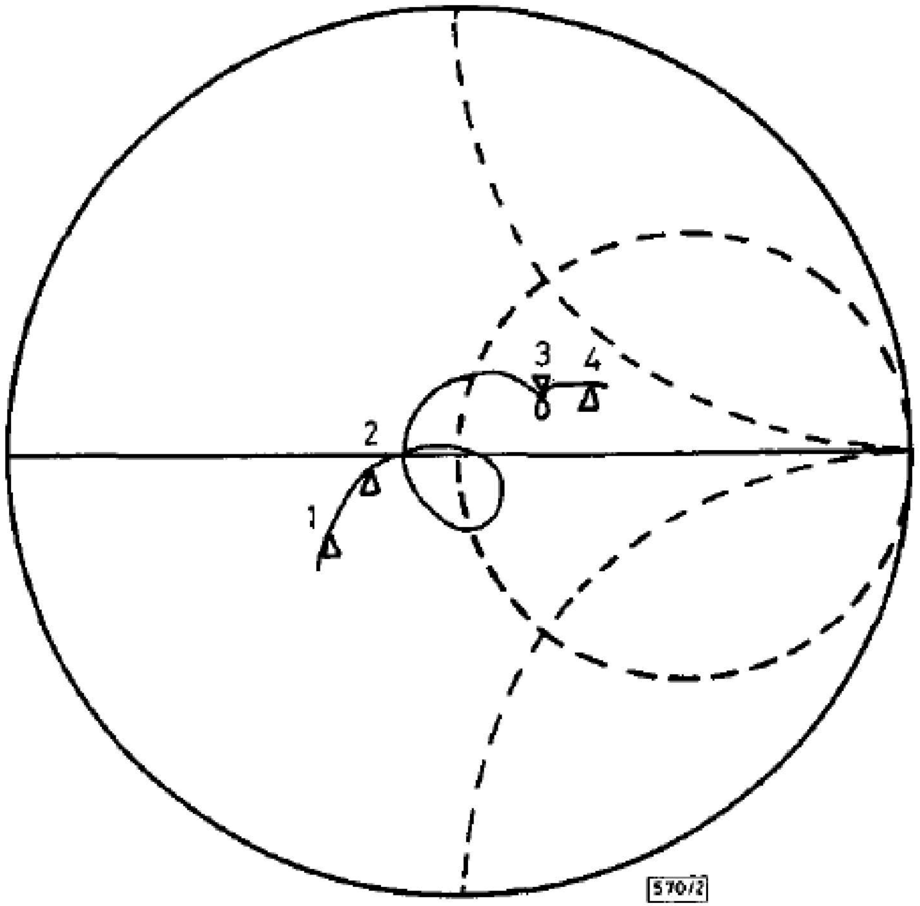


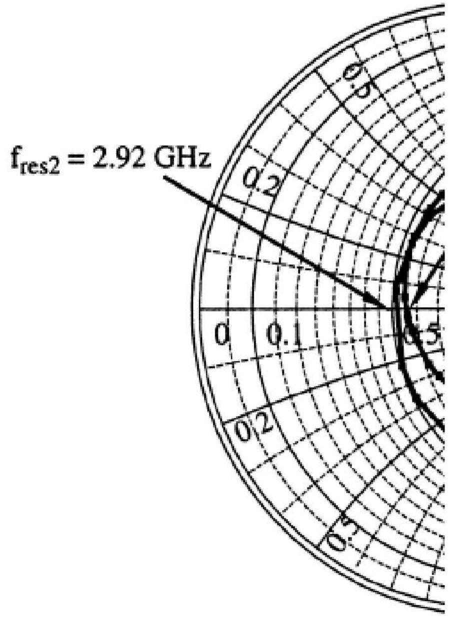
Fig. 2 *Measured impedance loci for h = 1.06" (≃0.08λ at 900 MHz)*

T. Huynh and K. F. Lee, "Single-layer single-patch wideband microstrip antenna," in *Electronics Letters*, vol. 31, no. 16, pp. 1310-1312, 3 Aug. 1995.

Previous design guides

Table 10.7. Design parameters for 2 GHz U-slot patches. (All dimensions in mm.)

ε_r	W	L	W_s	L_s	b	$c_x = c_y$	F	h	d_p	Bandwidth
2.33	55.85	40.36	21.71	27.92	6.21	3.11	20.18	12.43	1.53	27.13%
4.0	41.84	30.22	16.26	20.94	4.63	2.34	15.13	10.81	0.76	25.18%
9.8	25.85	18.64	10.04	12.92	2.88	1.44	11.12	9.00	0.36	16.07%



DI

ε_r	
1.0	8
2.33	4
4.0	3
9.8	2
2.33	5

Table 10.8. Design parameters for 3 GHz U-slot patches. (All dimensions in mm.)

ε_r	W	L	W_s	L_s	b	$c_x = c_y$	F	h	d_p	Bandwidth
2.33	37.23	26.90	14.47	18.61	4.14	2.07	13.45	13.45	1.02	27.13%
4.0	27.89	20.15	10.84	13.96	3.09	1.56	9.06	8.2	0.51	20.77%
9.8	17.23	12.43	6.69	8.61	1.92	0.96	7.34	6.00	0.12	15.95%

Table 10.9. Design parameters for 4 GHz U-slot patches. (All dimensions in mm.)

ε_r	W	L	W_s	L_s	b	$c_x = c_y$	F	h	d_p	Bandwidth
2.33	27.93	20.18	3.11	13.96	3.11	1.55	10.09	6.21	0.76	26%
4.0	20.92	15.11	8.13	10.47	2.31	1.17	6.79	5.5	0.38	24.4%
9.8	12.92	9.32	5.02	6.46	1.44	0.72	5.56	4.5	0.09	15.77%

IAL PARAMETERS

	Offset+
)	0
)	0
)	+
	–
	0
	+
	–
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	–
	v
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	–
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	v
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S. Weigand, G. H. Huff, K. H. Pan and J. T. Bernhard, "Analysis and design of broad-band single-layer rectangular U-slot microstrip patch antennas," in IEEE TAP, vol. 51, no. 3, March 2003.

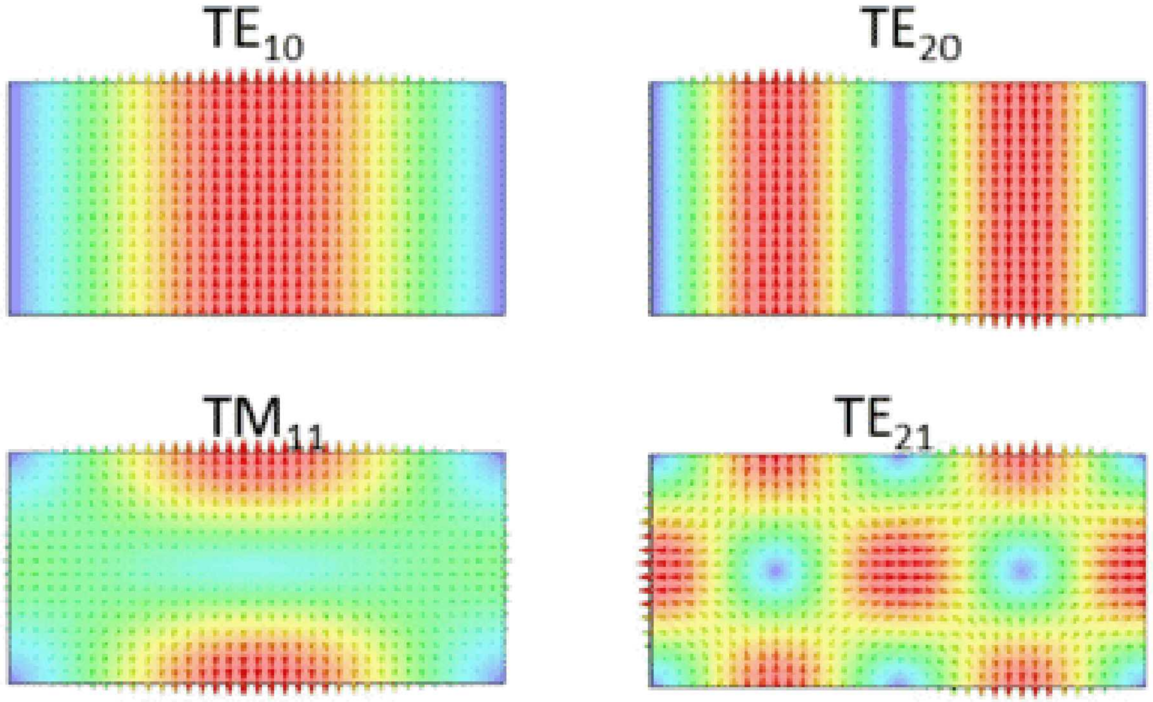
V. Natarajan and D. Chatterjee, "An Empirical Approach for Design of Wideband, Probe-Fed, U-Slot Microstrip Patch Antennas on Single-layer, Infinite, Grounded Substrates," ACES Journal, vol. 18, no. 3, Nov 2003.

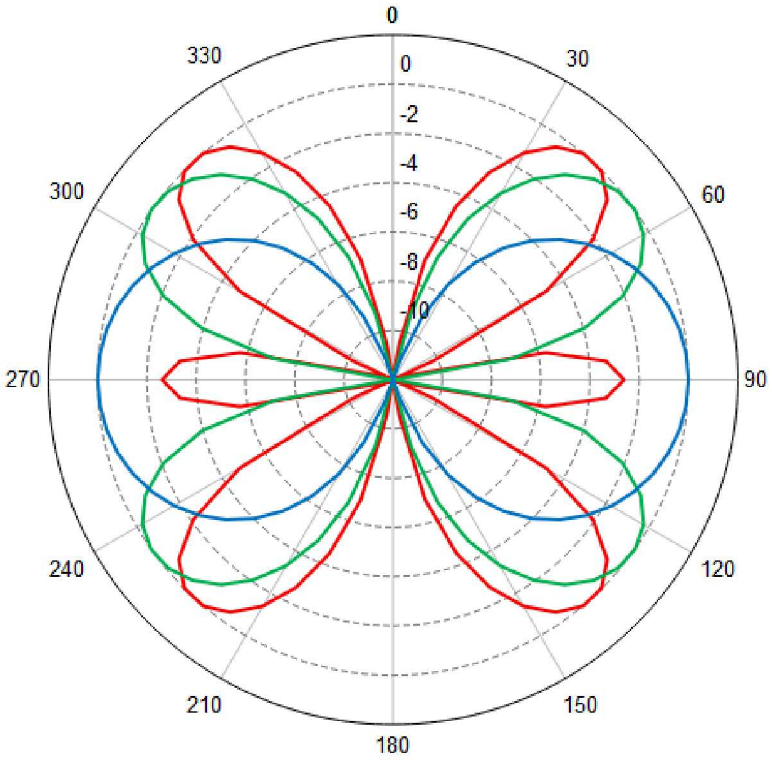
K.F. Lee, K. M. Luk and H. W. Lai, "Broadbanding Techniques II --- The U-slot Patch Antenna" in Microstrip patch antennas, 2nd ed., Singapore: World Scientific, 2018, ch. 10.

Intro to Characteristic Mode Analysis (CMA)

Characteristic modes are sets of currents/fields on a structure that satisfy the boundary conditions…

Similar in concept to waveguide modes, but are suited to radiation/scattering problems

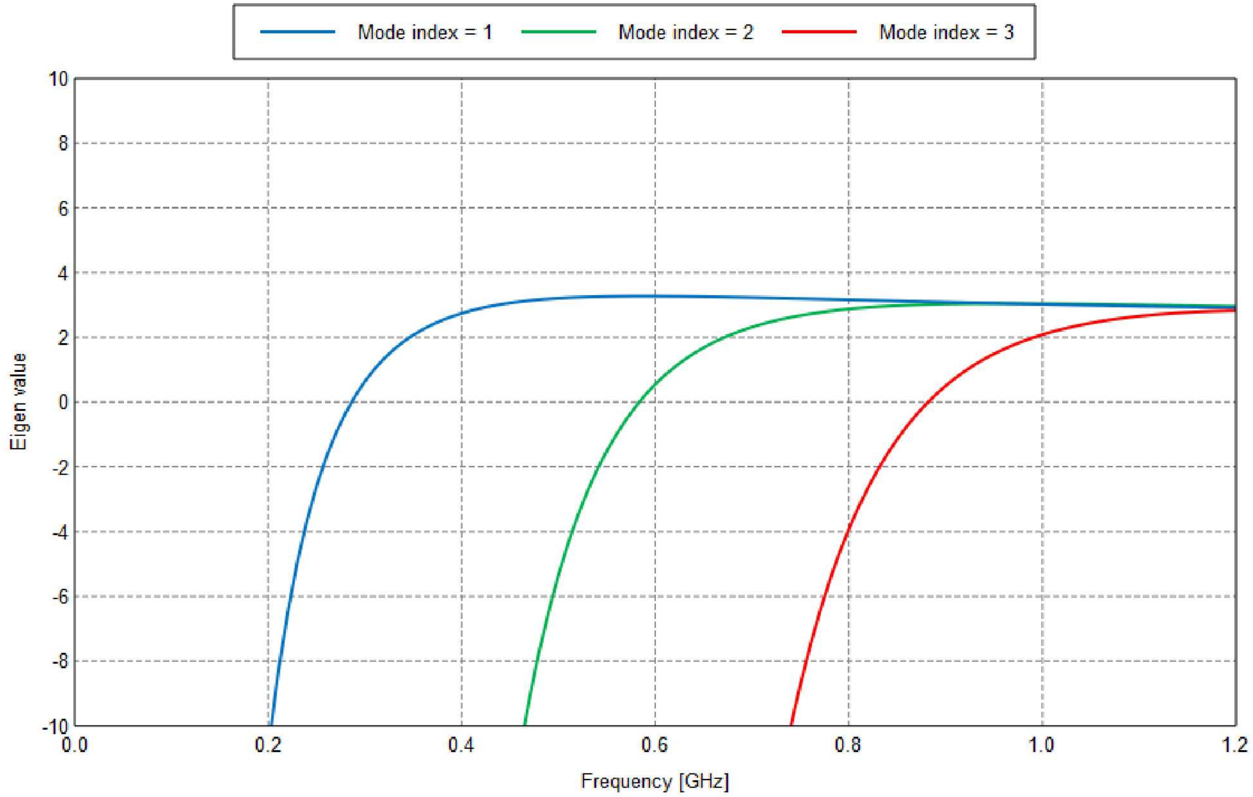




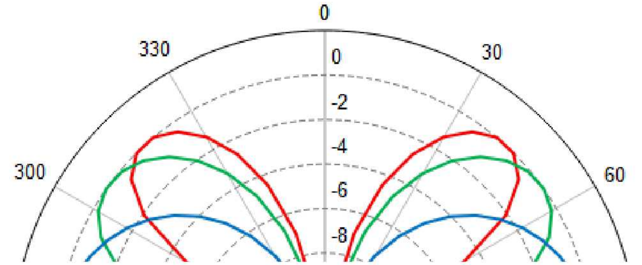
$$\nabla_t^2 e + \beta^2 e = 0$$

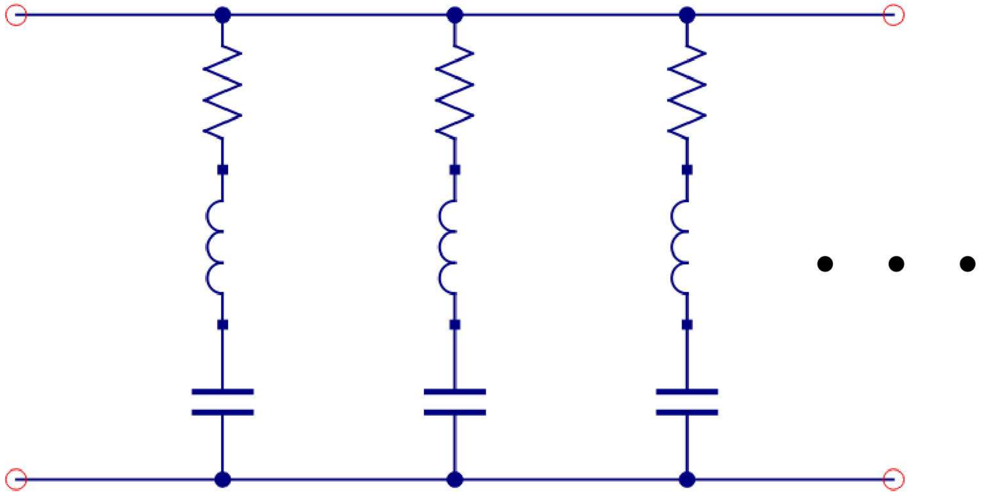
$$[X]\, J_n = \lambda_n\, [R]\, J_n$$

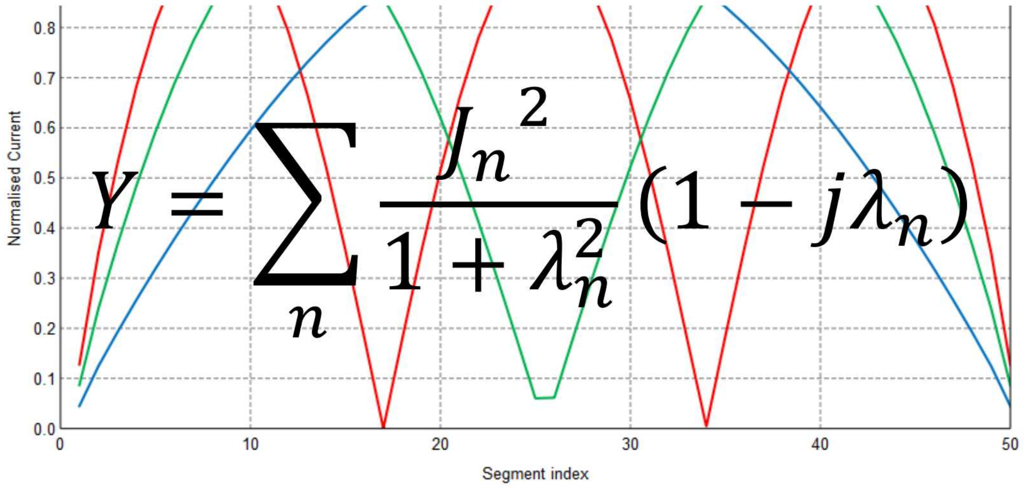
CMA example: 0.5 meter wire dipole



$$\omega\,(W_m - W_e) = \lambda_n$$

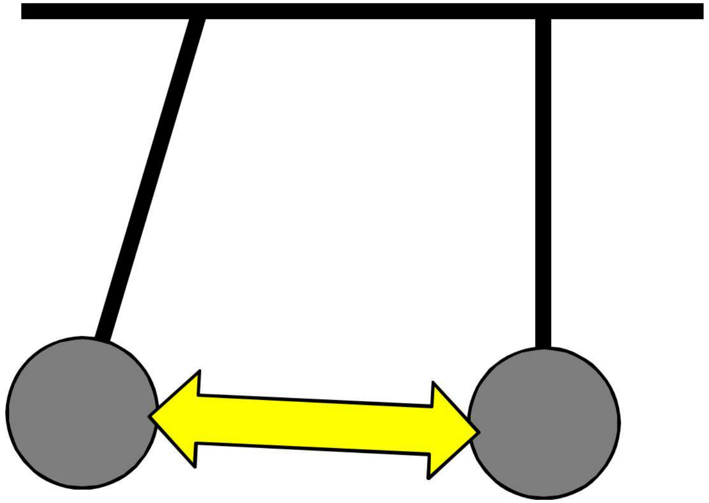


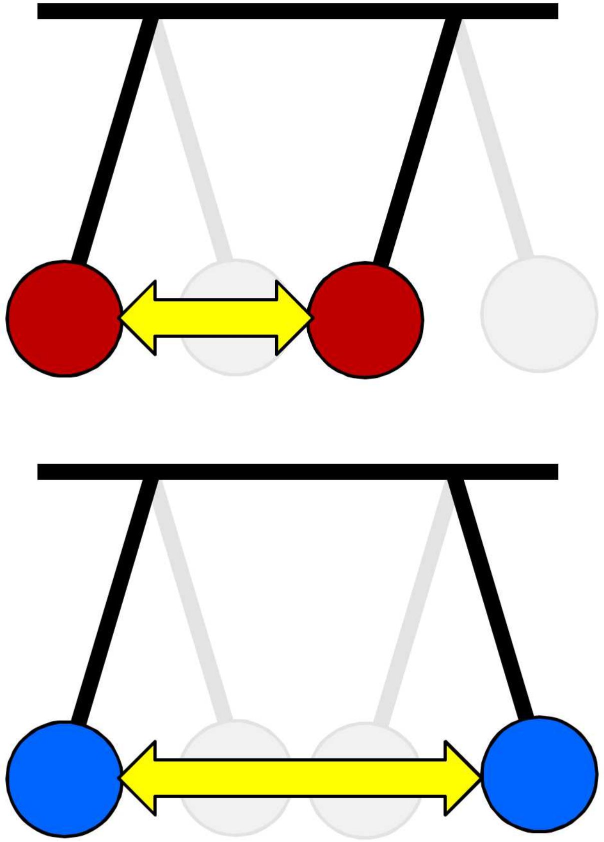




$$Y = \sum_n \frac{J_n{}^2}{1+\lambda_n^2}(1 - j\lambda_n)$$

CMT analyses the motion of a system of two coupled resonators as the combination of in-phase and anti-phase modes of motion

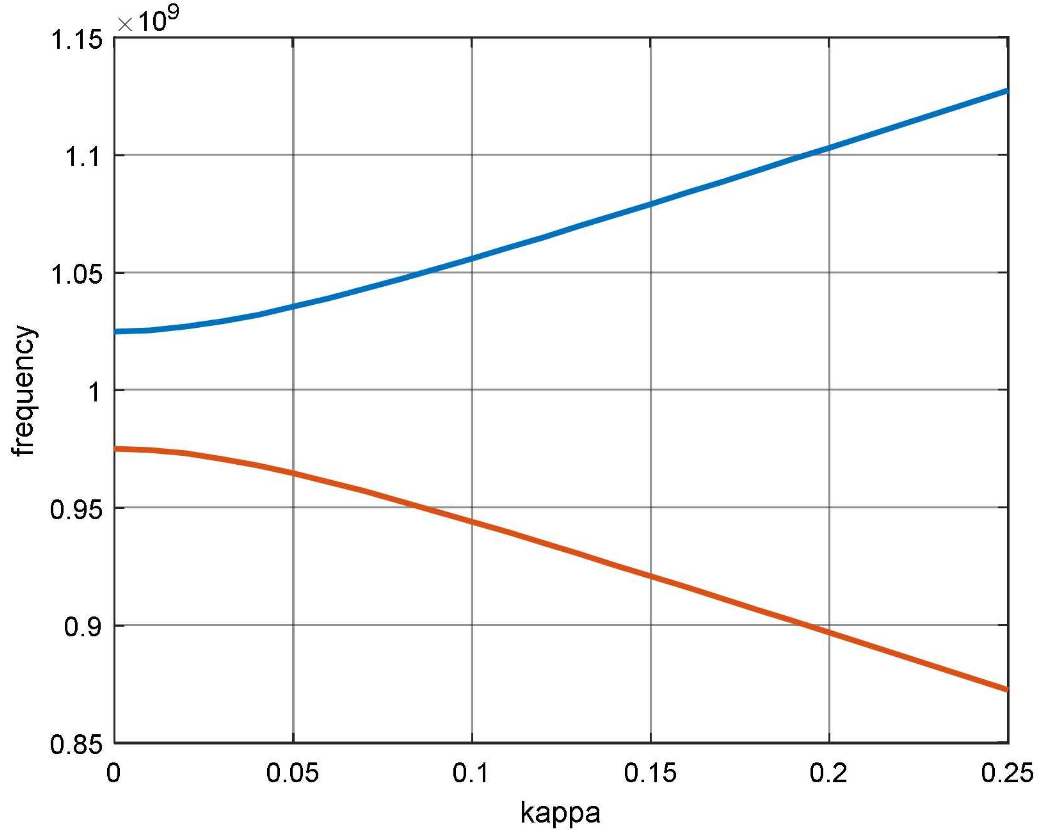


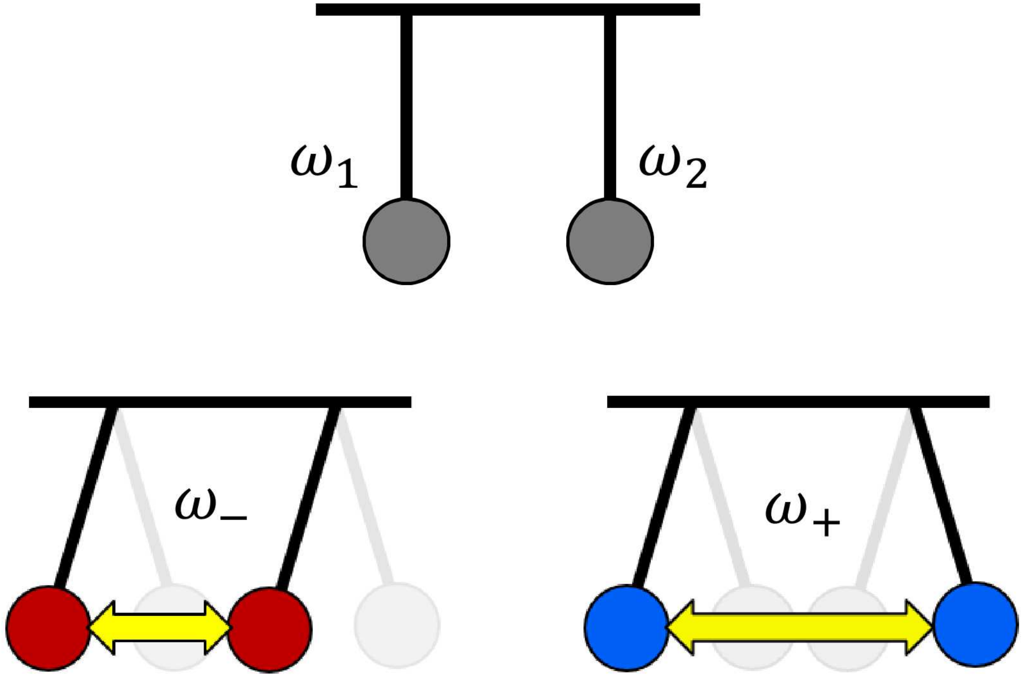


Coupled modes illustration

https://www.youtube.com/watch?v=gbJYK7q5ejY

Coupled mode frequency splitting

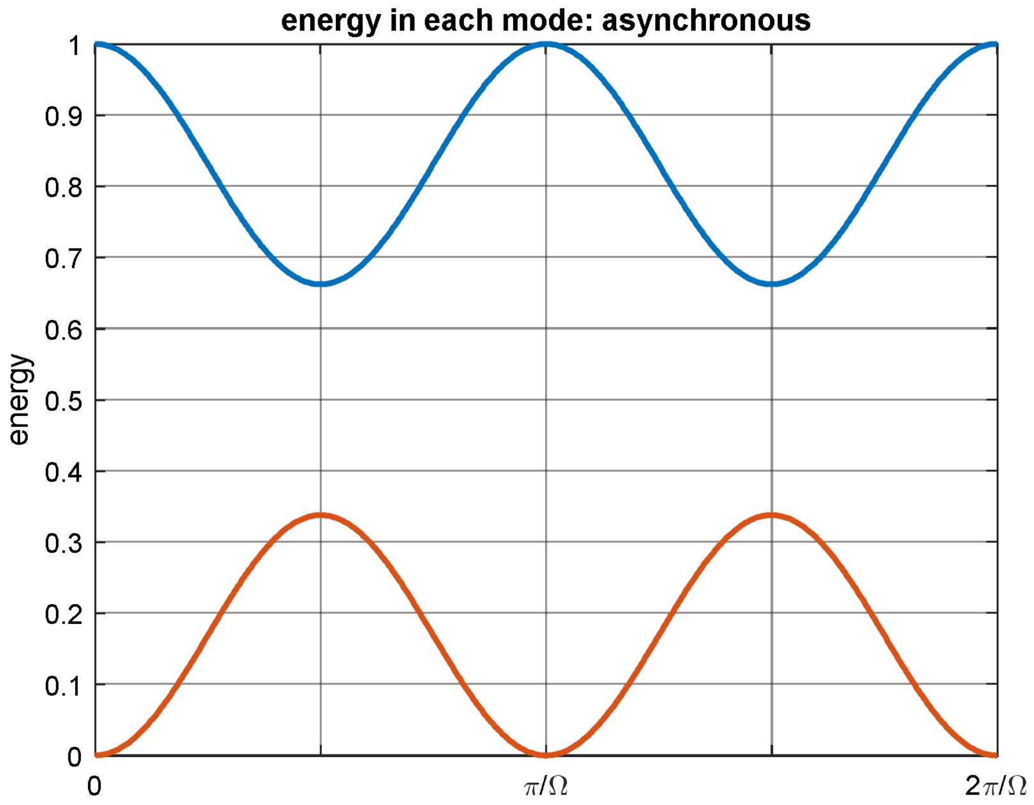




$$\omega_\pm = \left(\frac{\omega_2 + \omega_1}{2}\right) \pm \sqrt{\left(\frac{\omega_2 - \omega_1}{2}\right)^2 + |K|^2}$$

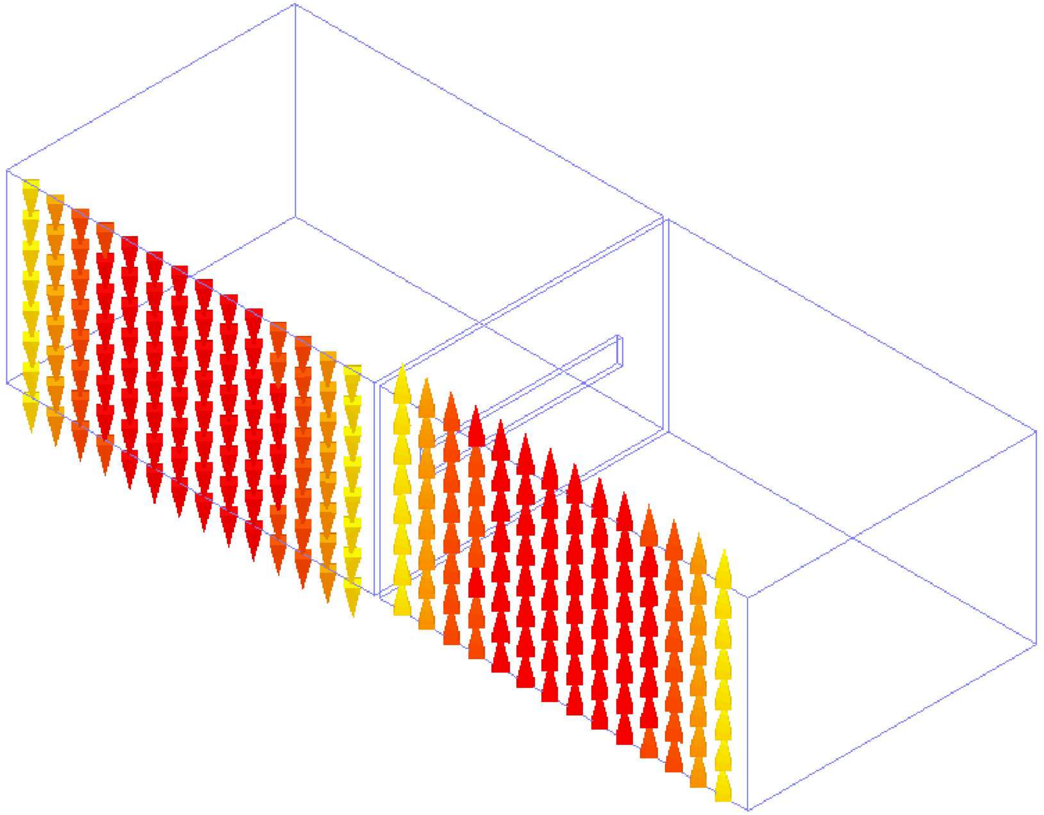
$$\kappa = \frac{{\omega_+}^2 - {\omega_-}^2}{{\omega_+}^2 + {\omega_-}^2} \qquad \kappa \sim \omega_0 K/2$$

Coupled mode energy exchange

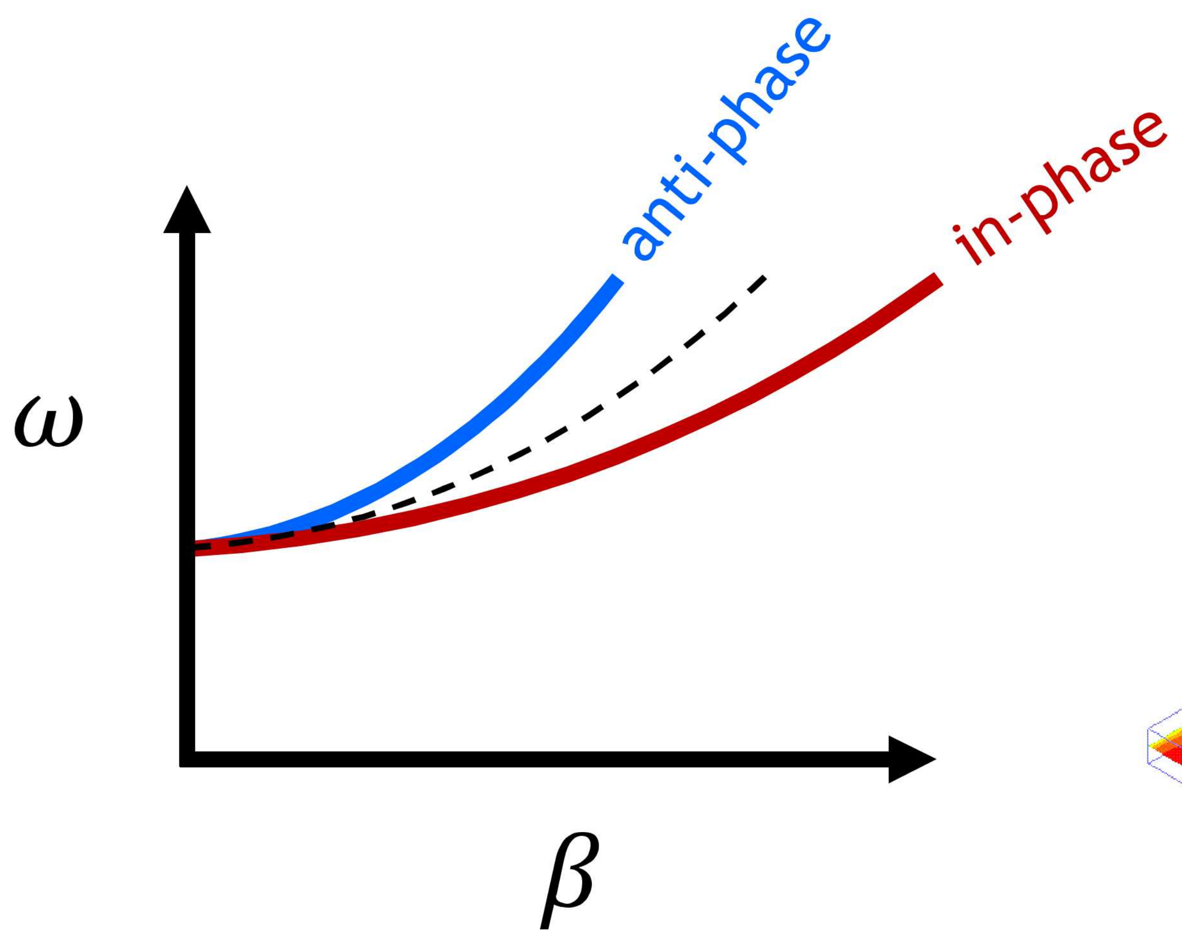


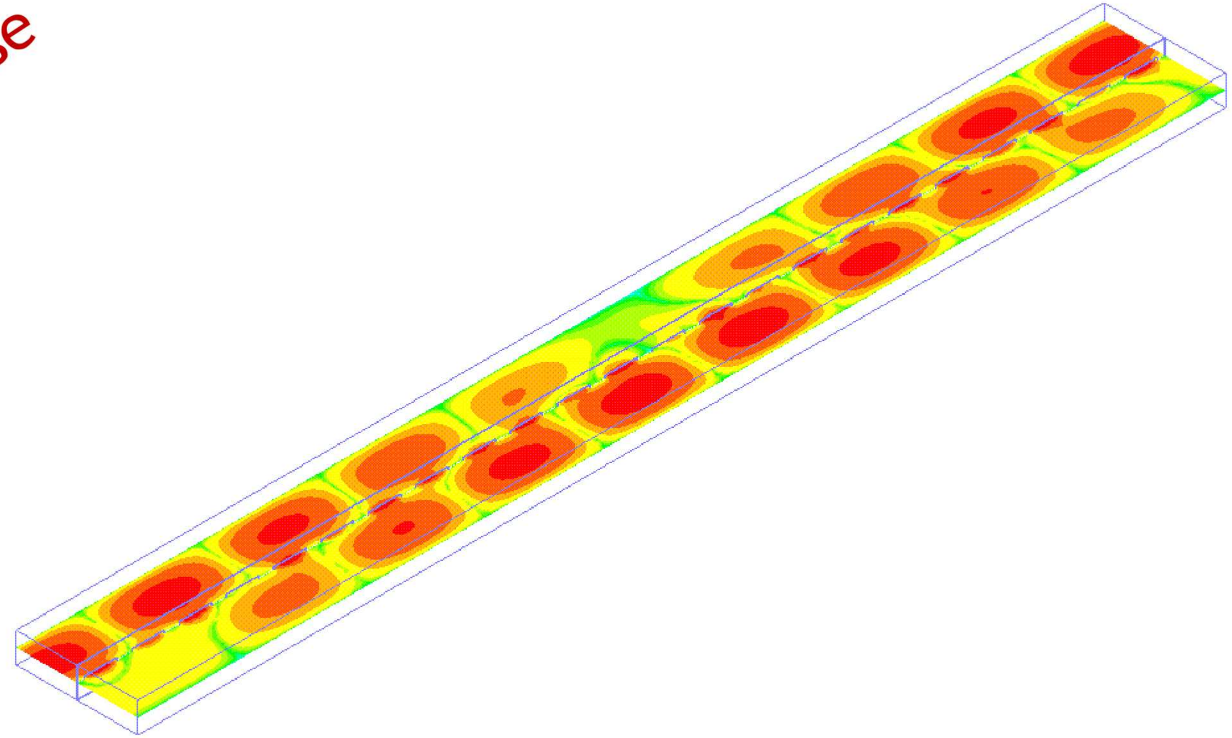
time →

space →

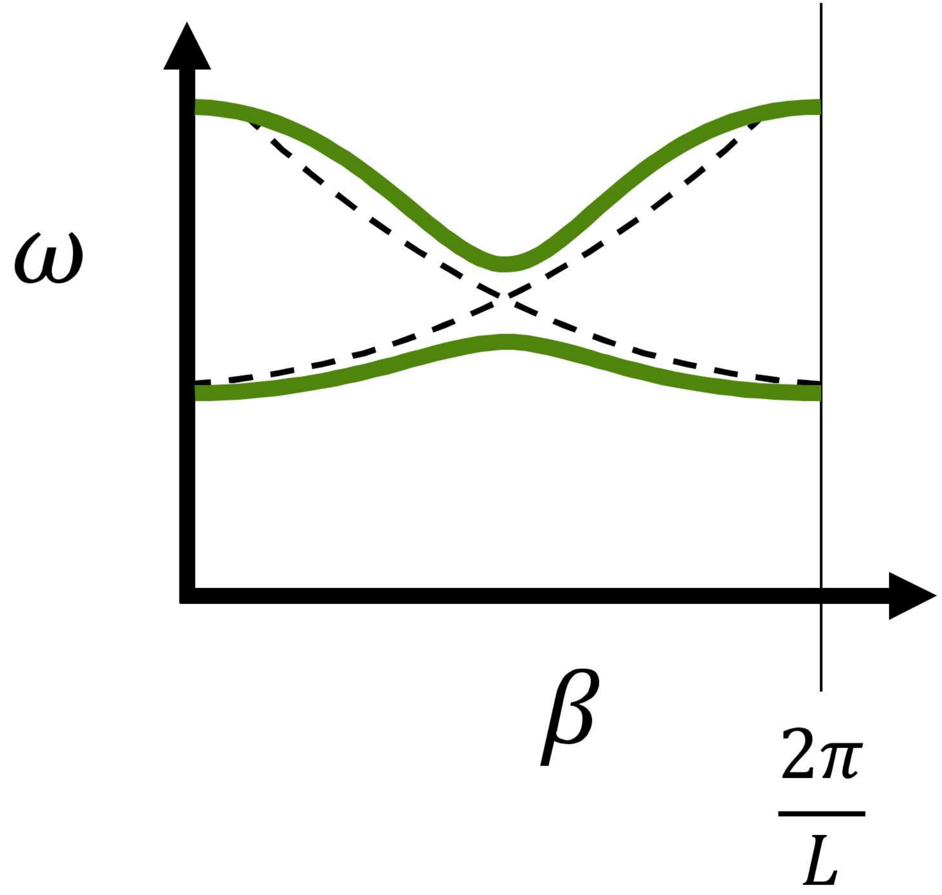


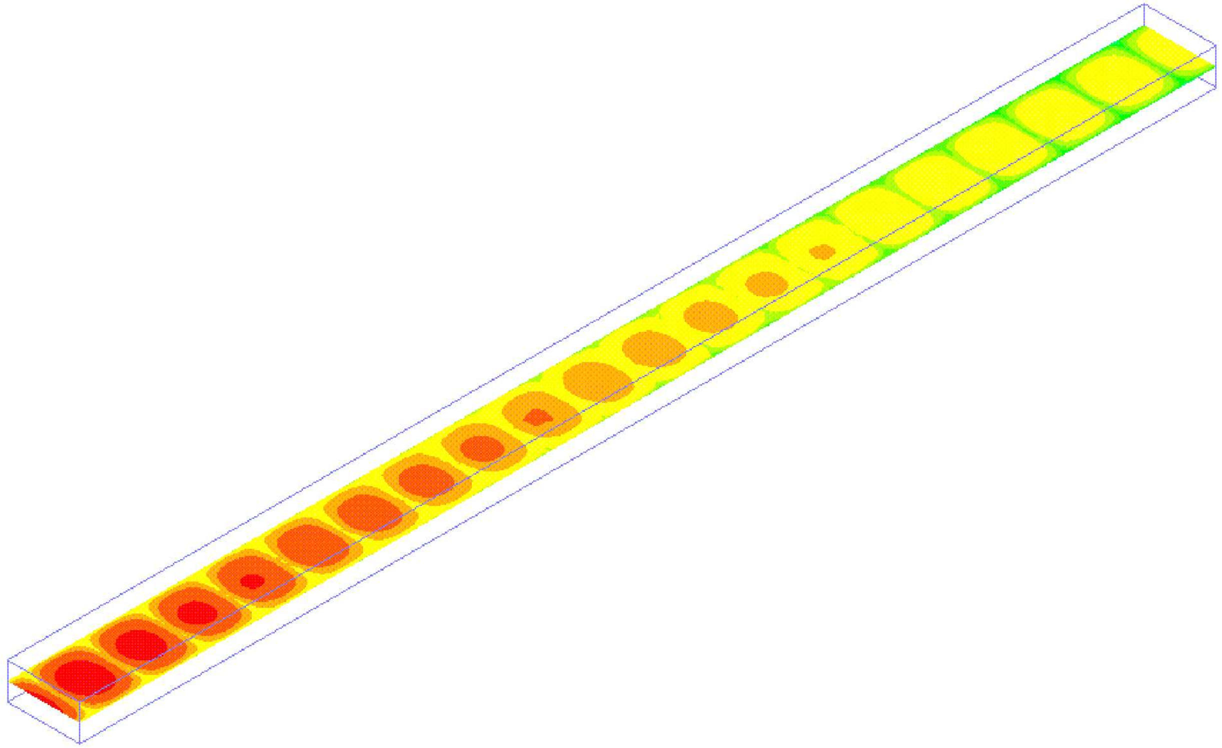
Coupling co-directional modes in space





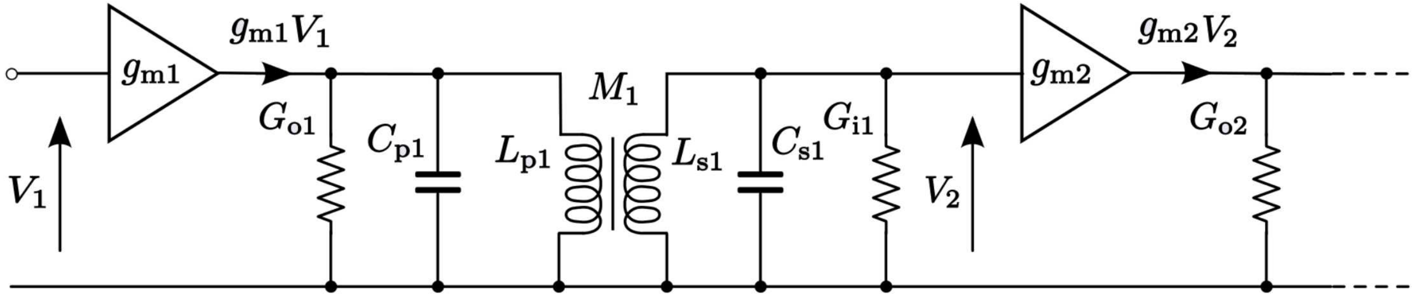
Coupling contra-directional modes in space

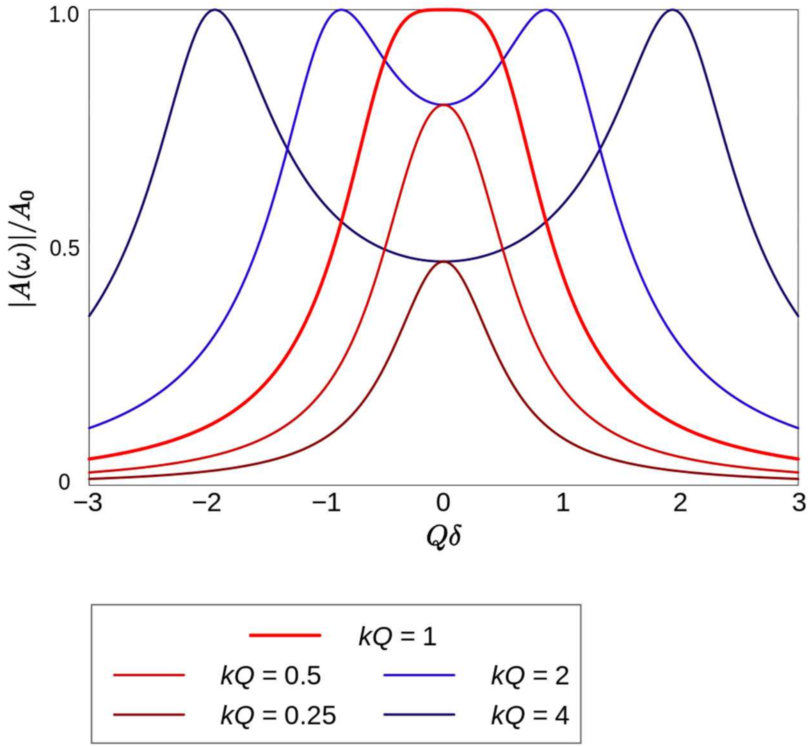




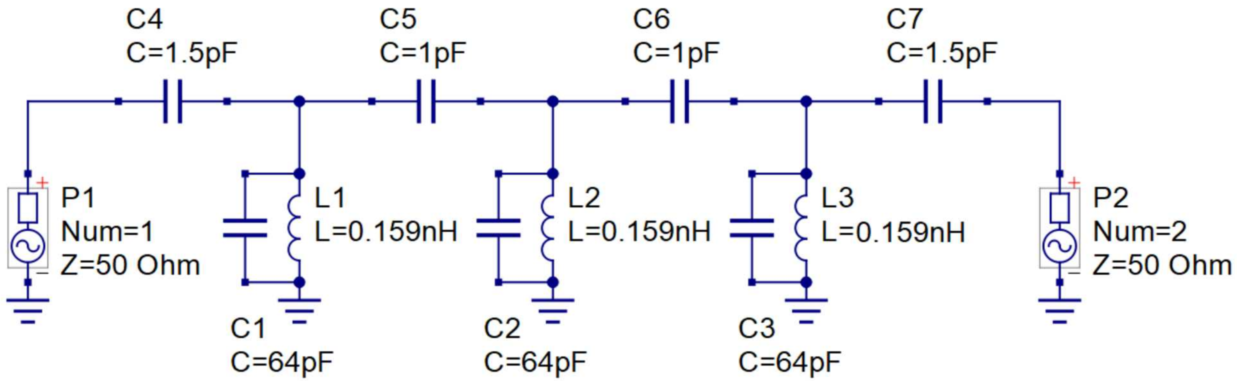
J.R. Pierce "Almost all about waves"

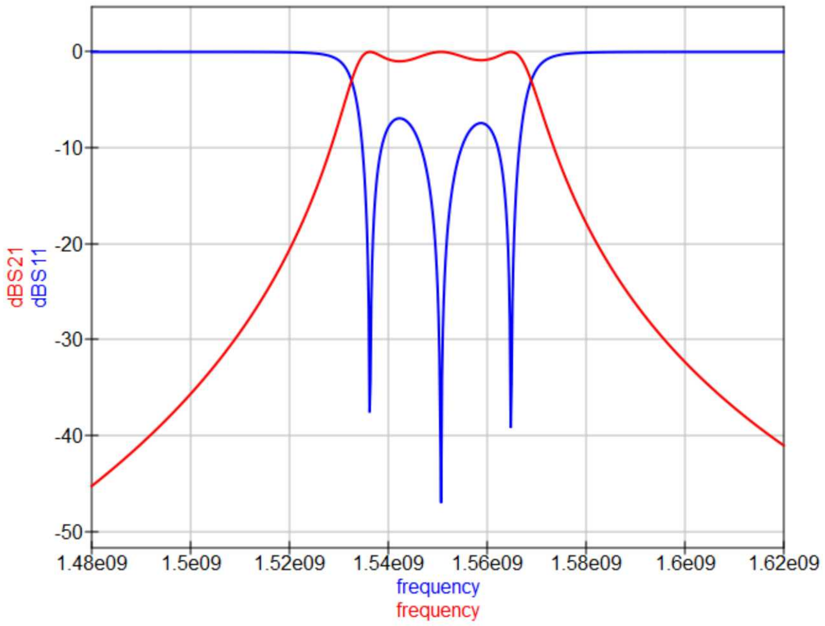
Coupled modes: time coupling in the frequency domain

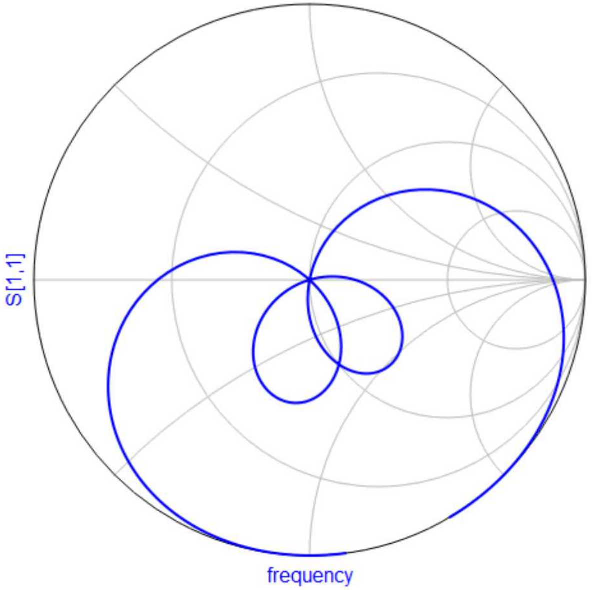




Coupled modes: time coupling in the frequency domain



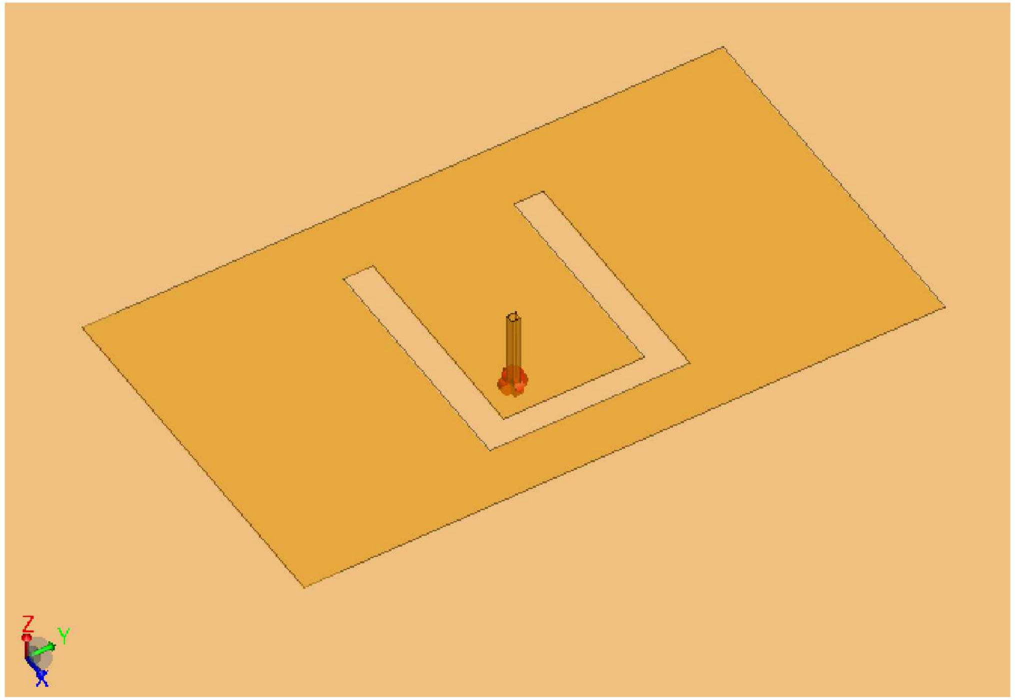


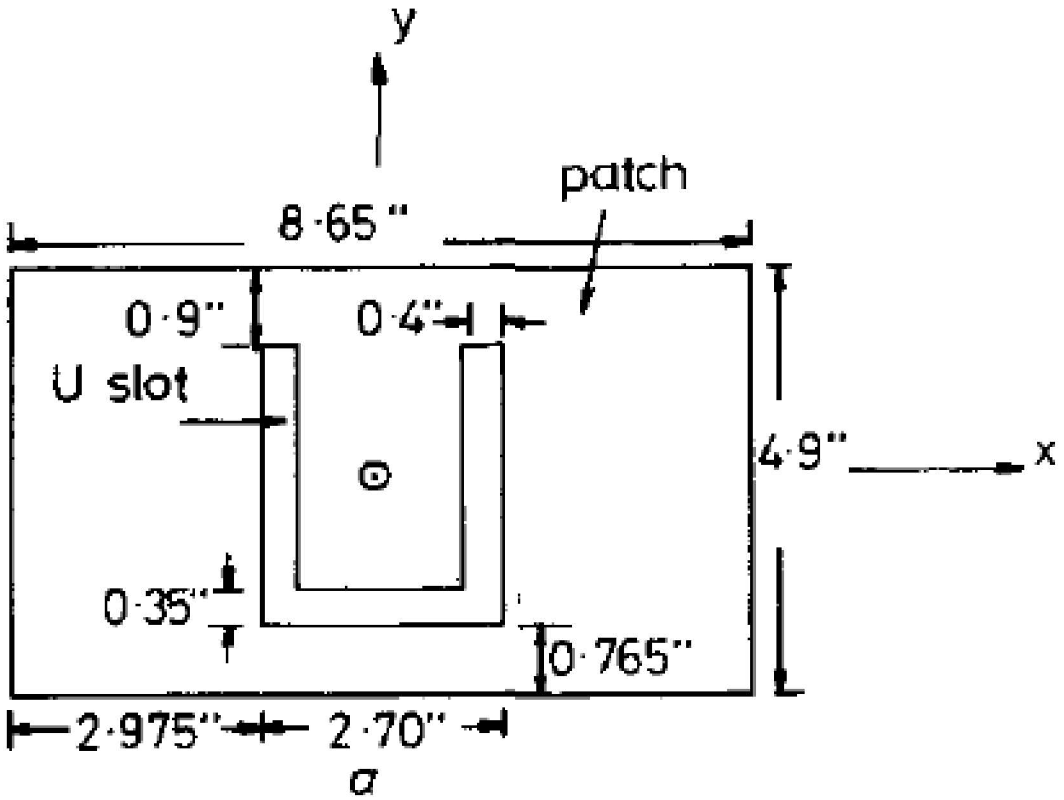


CMA of the U-slot patch

Using Feko (commercial MoM code)

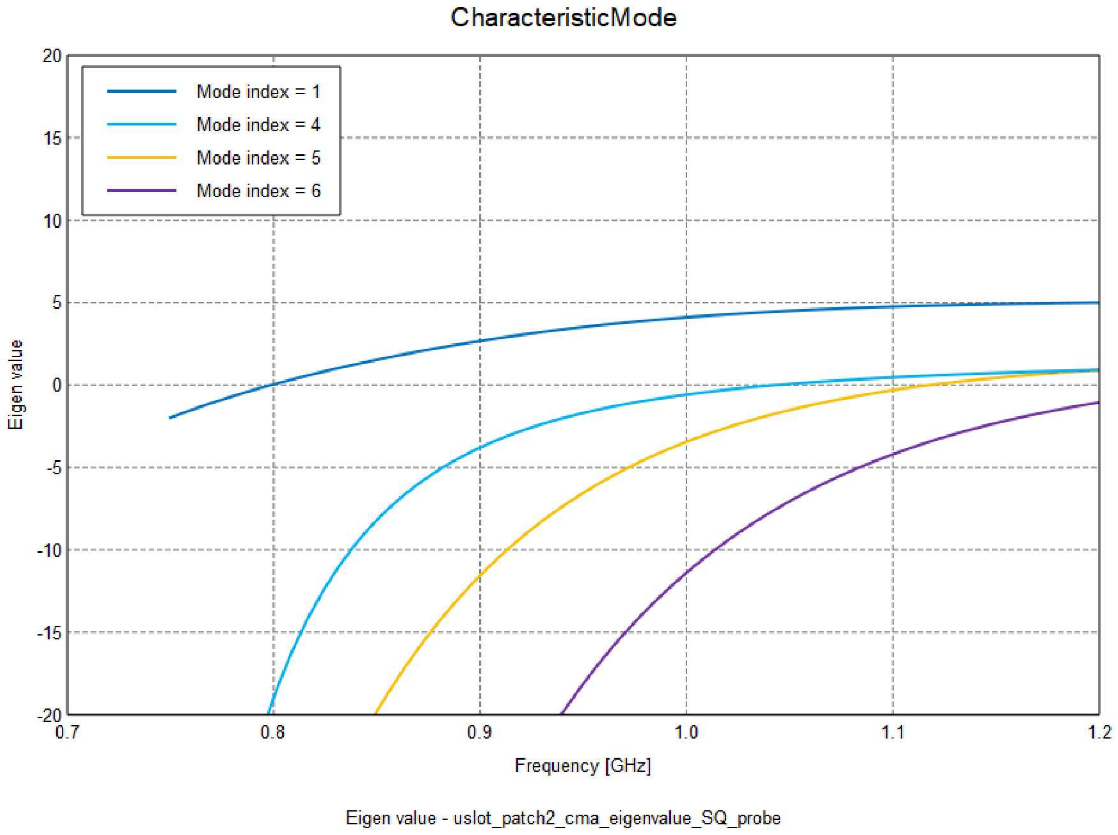
Model the Huynh & Lee geometry but model round probe as cuboid rather than cylinder

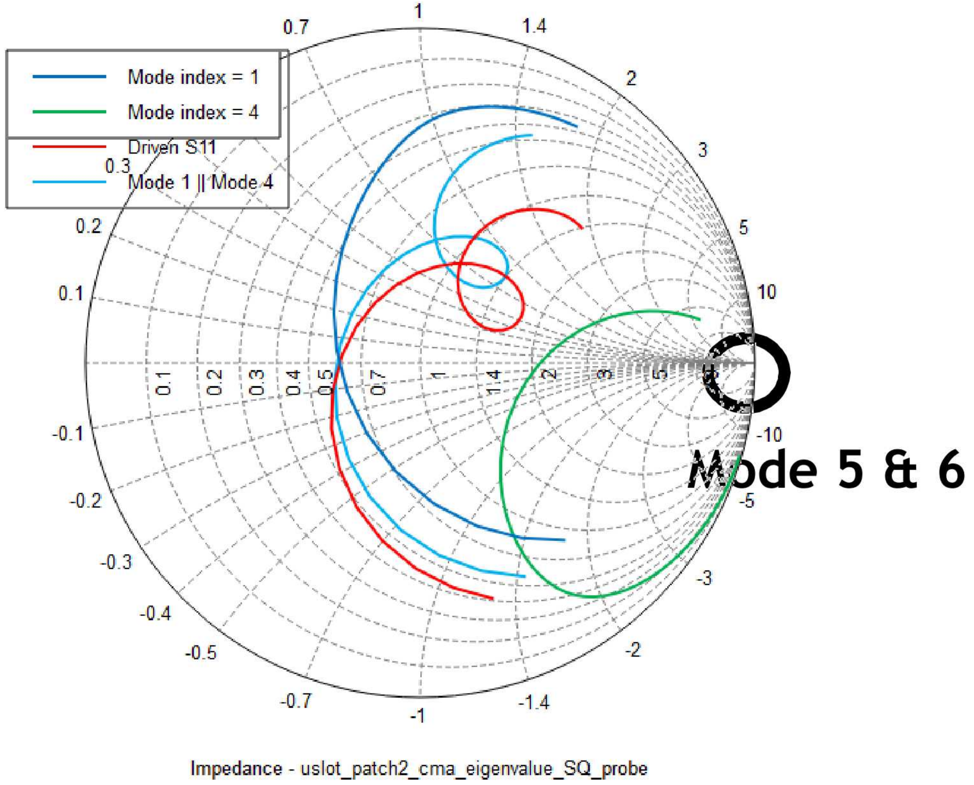




T. Huynh and K. F. Lee, "Single-layer single-patch wideband microstrip antenna," in *Electronics Letters*, vol. 31, no. 16, pp. 1310-1312, 3 Aug. 1995.

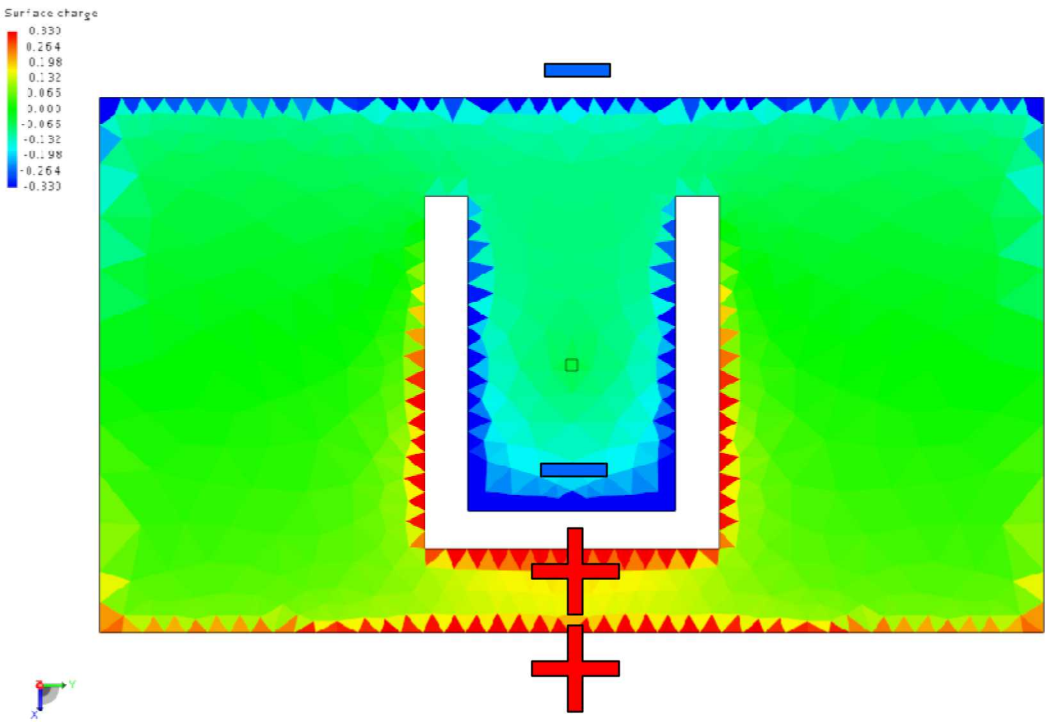
Which modes?


CharacteristicMode
Mode index = 1
Mode index = 4
Mode index = 5
Mode index = 6
Eigen value
Frequency [GHz]
Eigen value - uslot_patch2_cma_eigenvalue_SQ_probe


Mode index = 1
Mode index = 4
Driven S11
Mode 1 || Mode 4
Mode 5 & 6
Impedance - uslot_patch2_cma_eigenvalue_SQ_probe

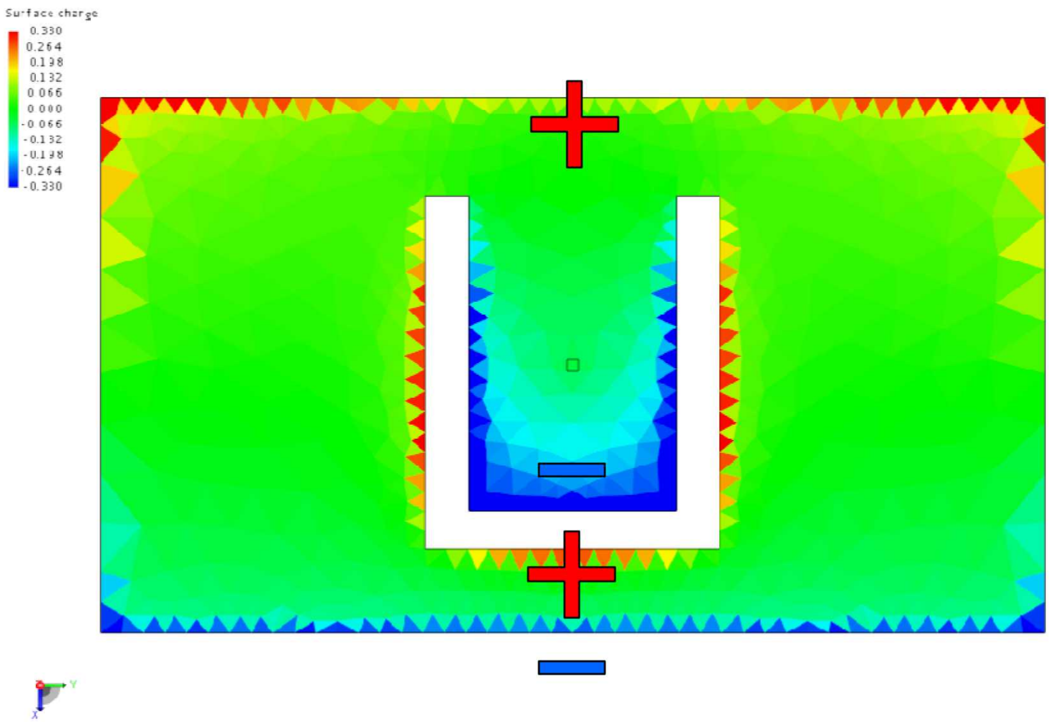
What are these modes?

Mode 1



in-phase

Mode 4

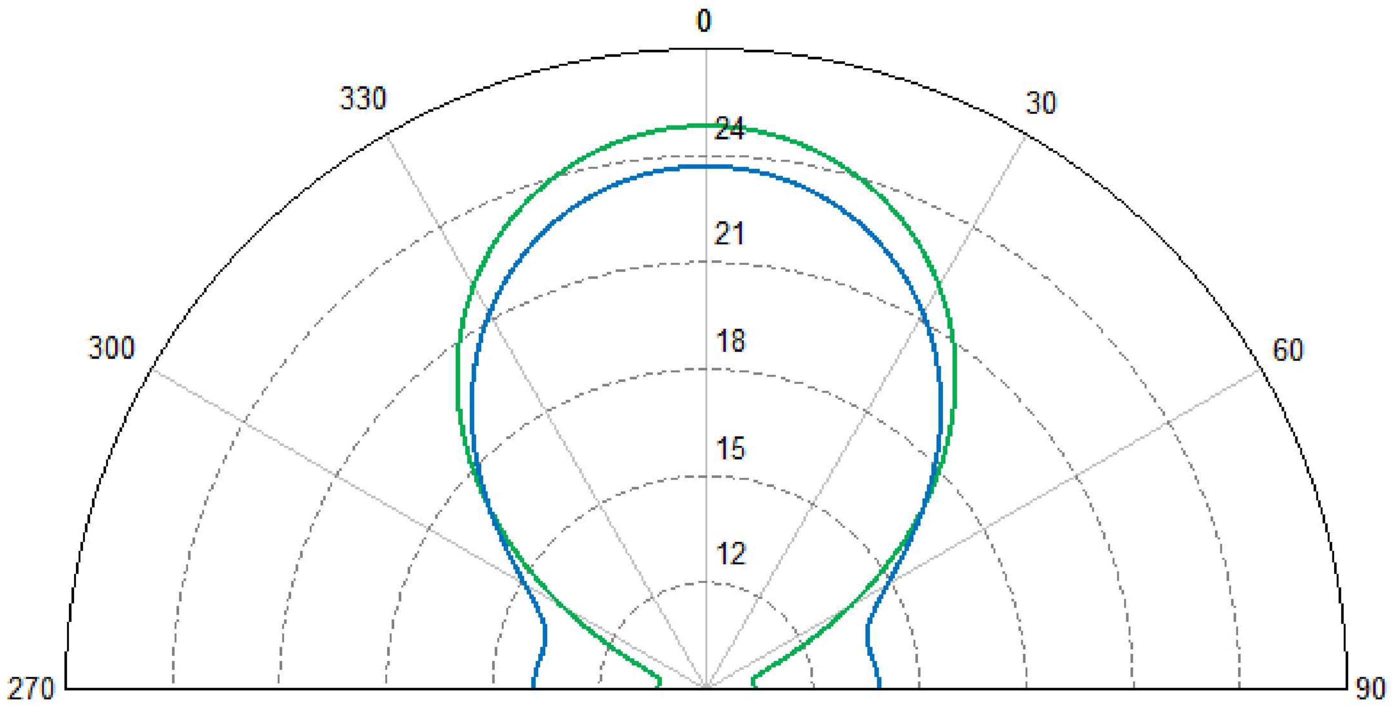


anti-phase

More about the modes

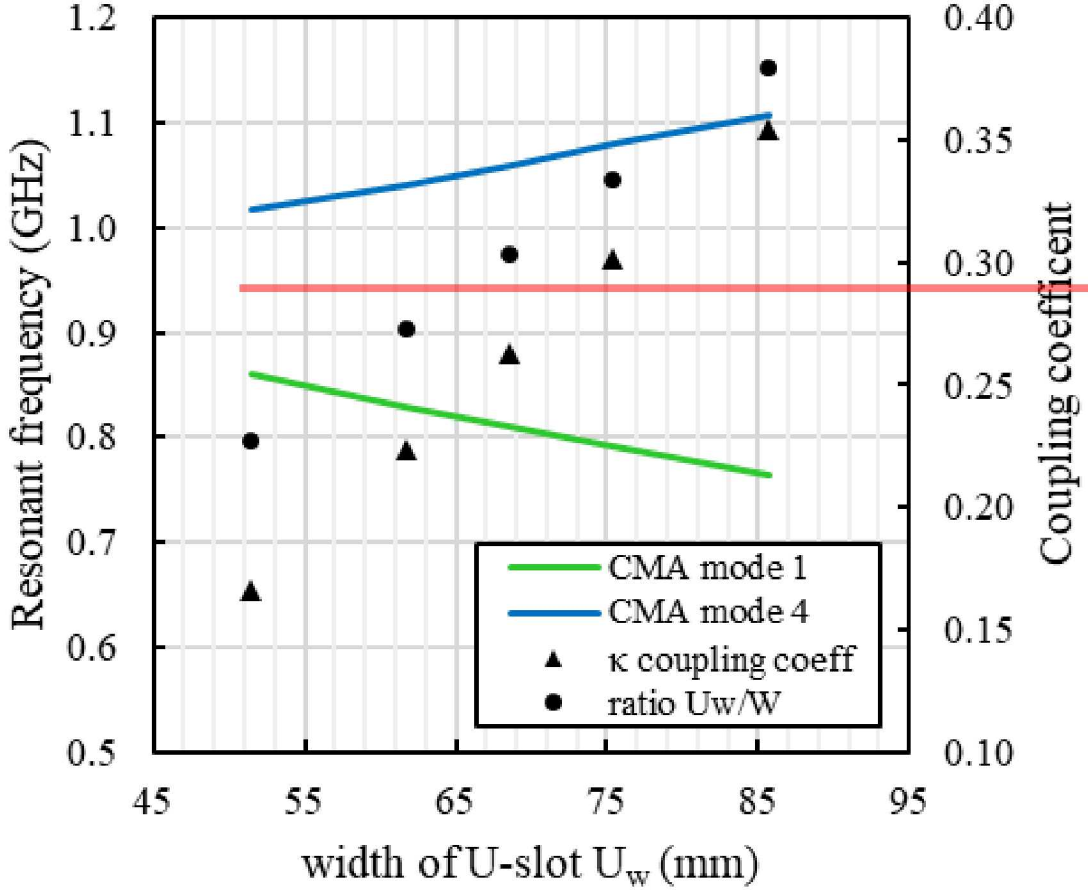
Similar broadside radiation patterns, co-polarized

Radiation from slot is likely relatively small



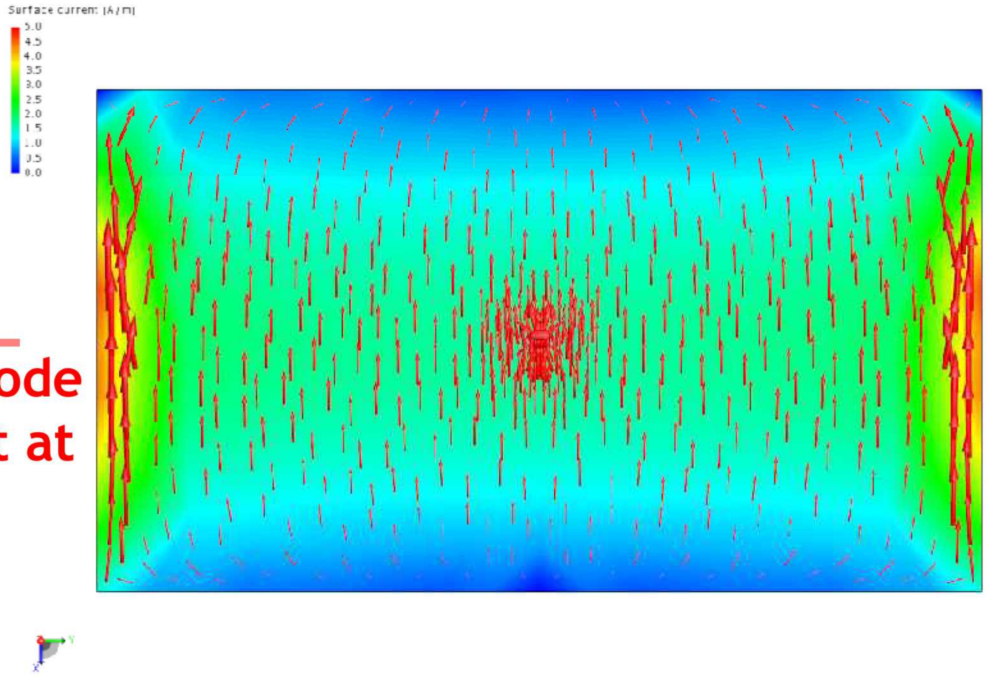
Electric field

Are they really coupled modes?



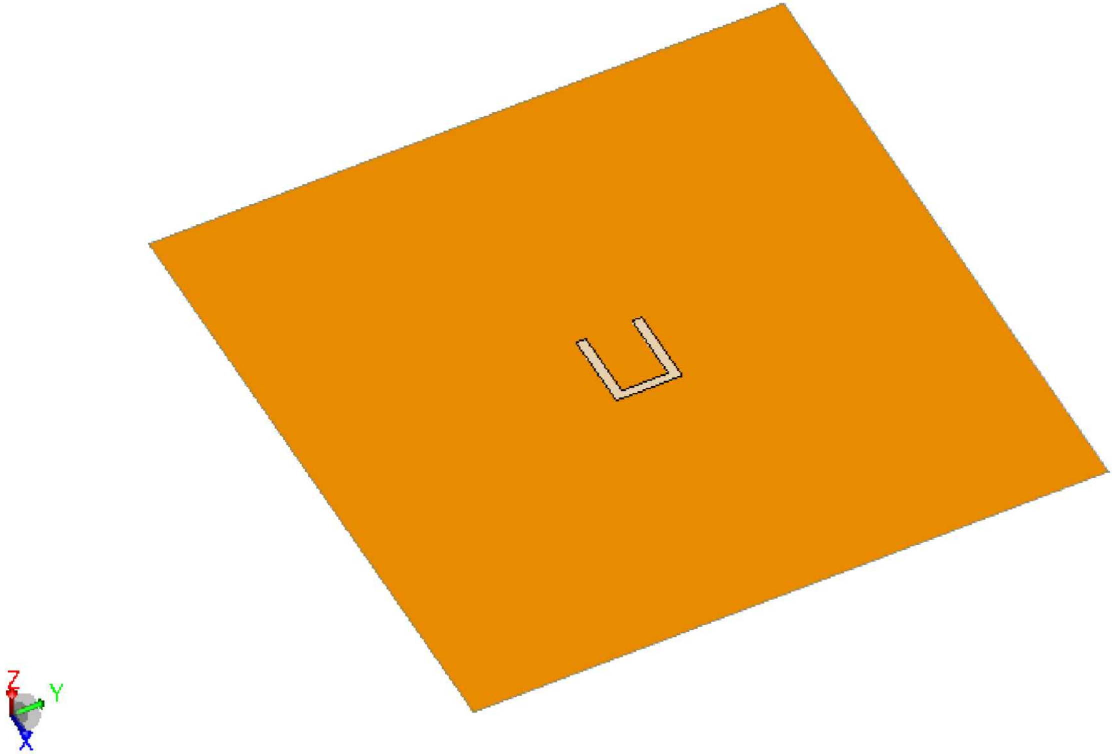
(Total length of slot kept constant.)

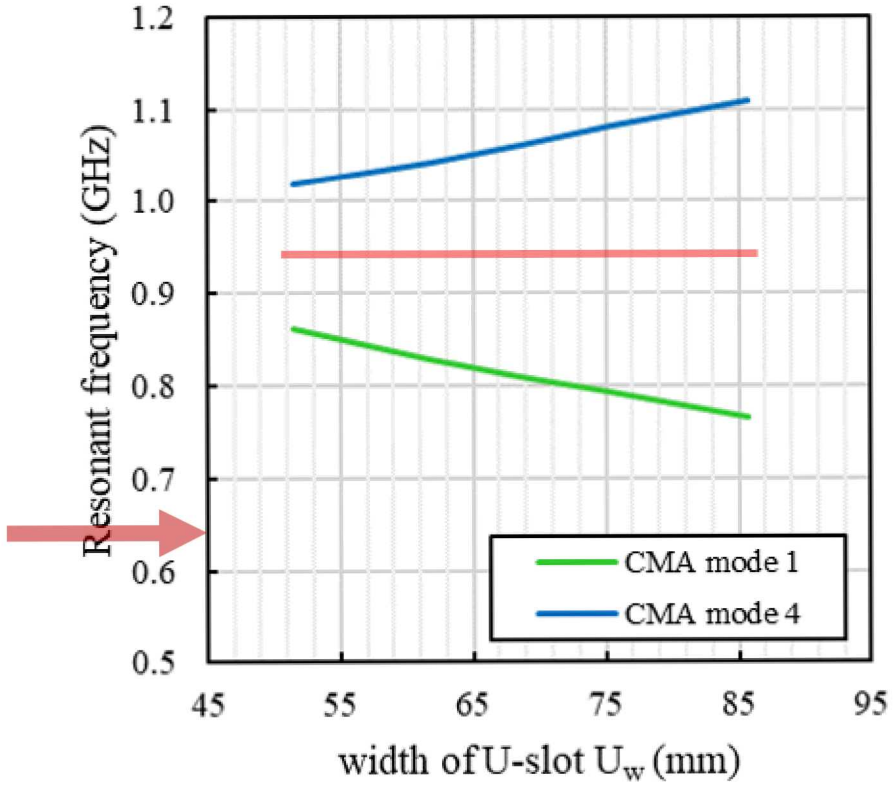
patch mode resonant at 946MHz



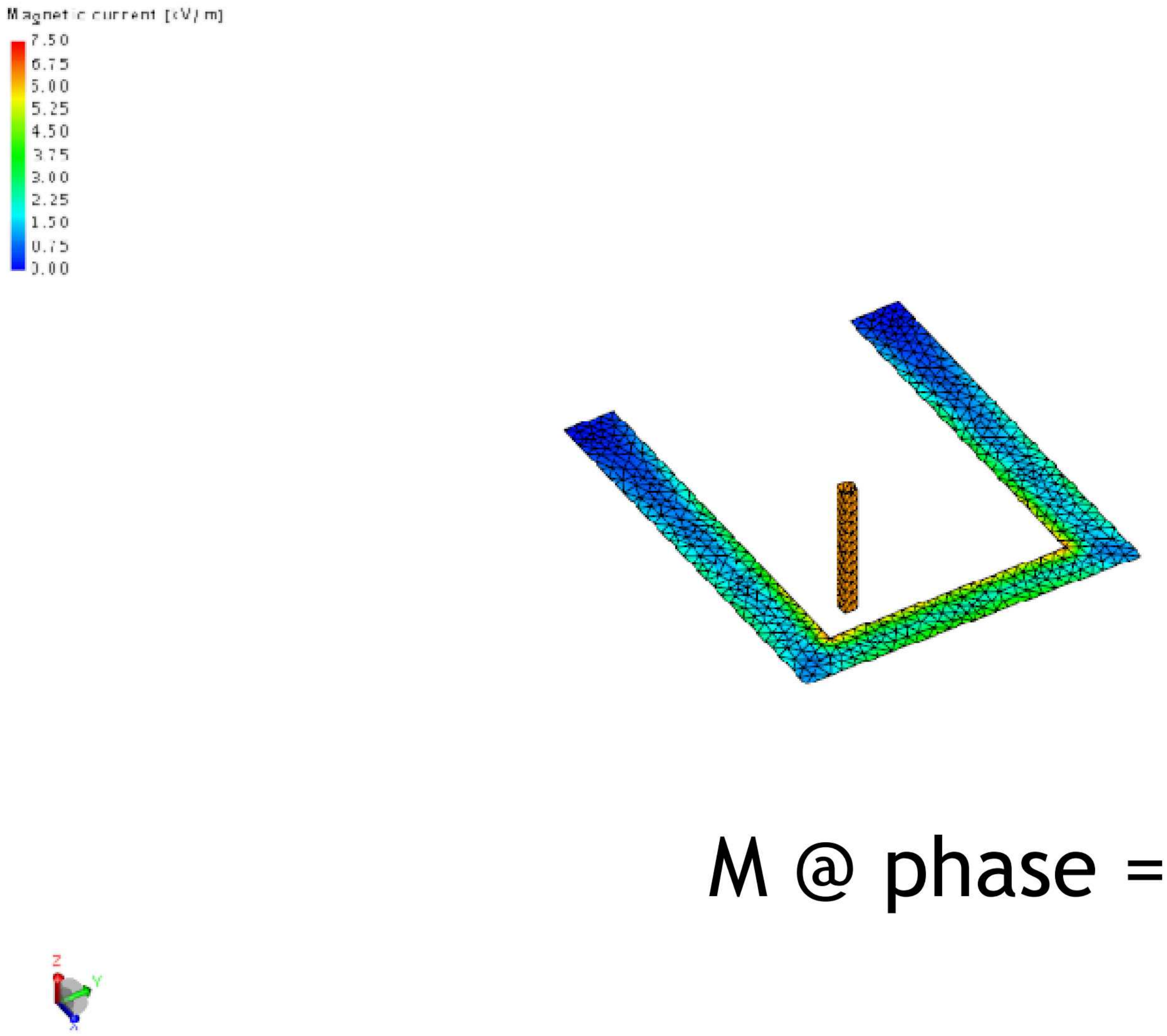
If it's synchronous coupling, then what is the other resonator?

Total length of slot is ~9” (23cm); gives CM resonance at ~640MHz (where slot is ~$\lambda/2$)…



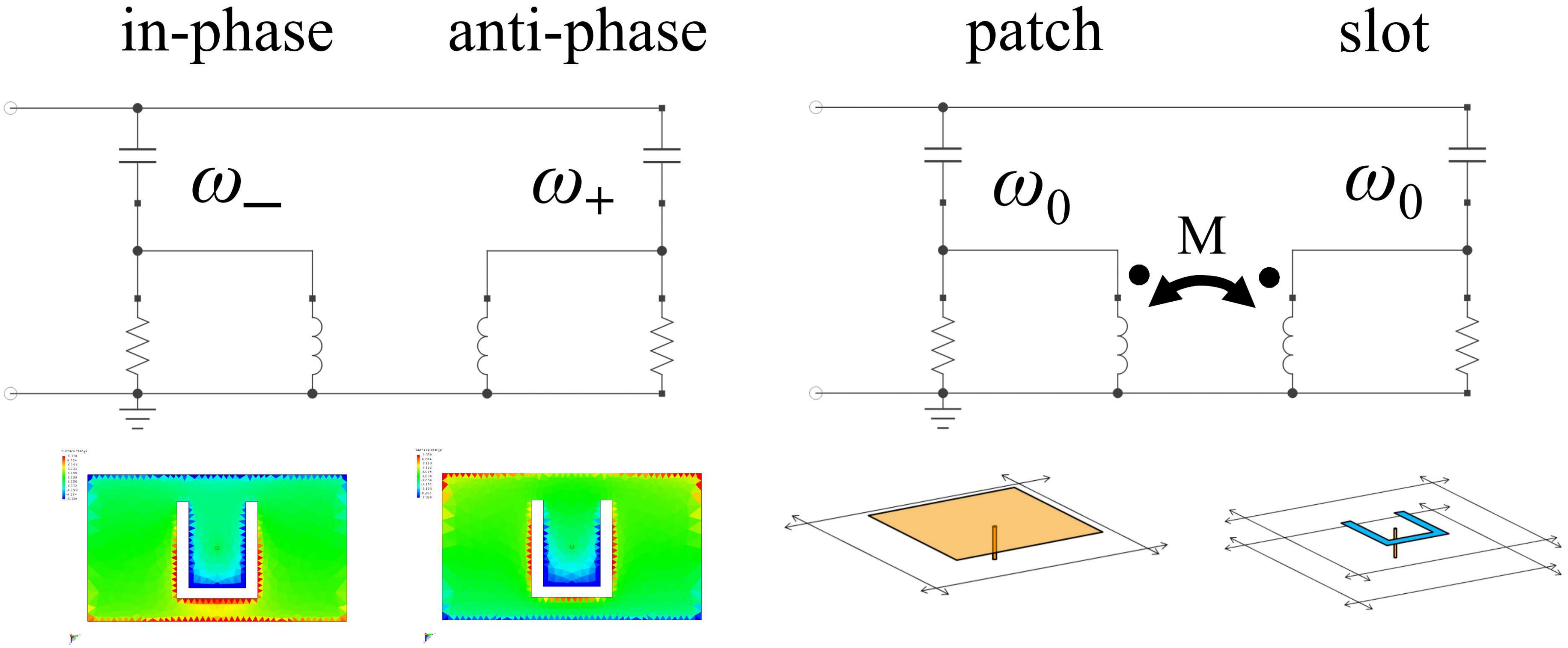


Uncoupled slot resonator, resonant at ~912MHz

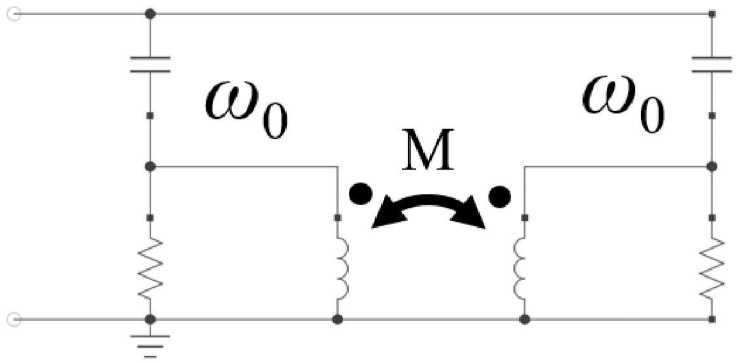


M @ phase = 90

Equivalent circuit modeling



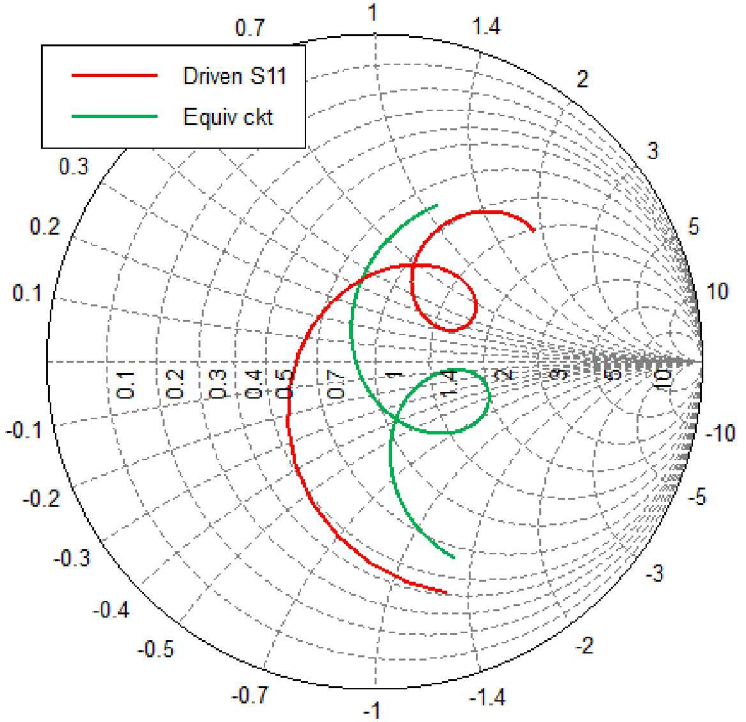
Equivalent circuit modeling

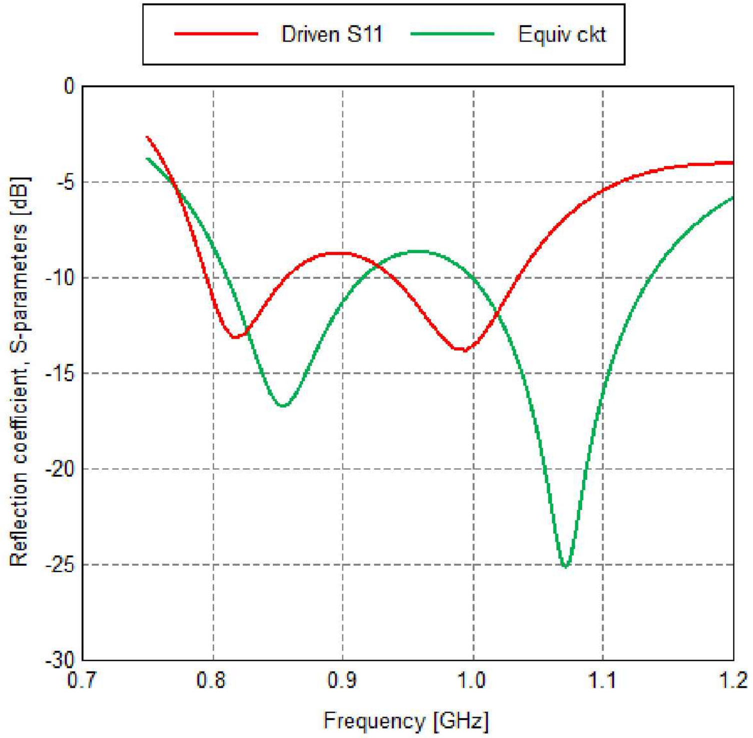


$$Y_c = G_0/Q' \qquad R_{\mathrm{hp}} = G_0/{Y_c}^2$$

$$C = Y_c/\omega_0 \qquad L = 1/(Y_c\, \omega_0)$$

Patch resonator		Slot resonator	
$\omega_0/2\pi$	946 MHz	$\omega_0/2\pi$	912 MHz
G_0	1 µS	G_0	34 mS
Q	4.5	Q	8.9
Q'	6.3	Q'	6.3
Rhp,patch	40 MΩ	Rhp,slot	1.18 kΩ
Lpatch	1.06 mF	Lslot	32.5 nH
Cpatch	0.0266 fF	Cslot	0.938 pF





Design Methodology

Place resonances

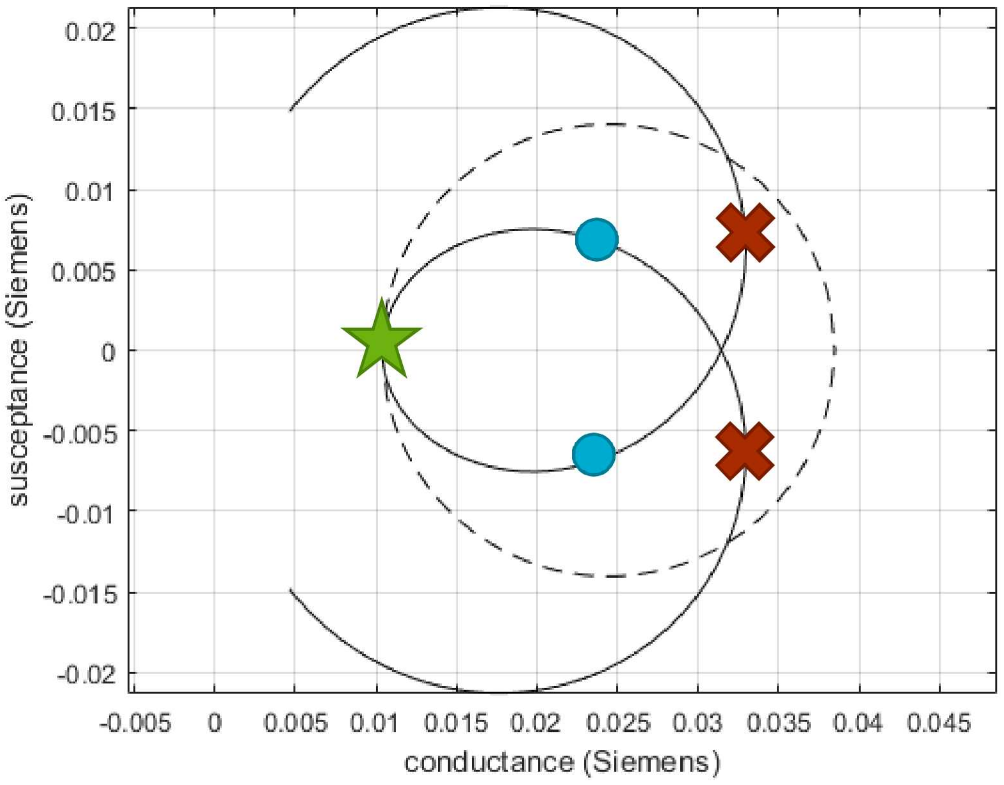
Design uncoupled patch and slot resonators with equal frequency & correct coupling

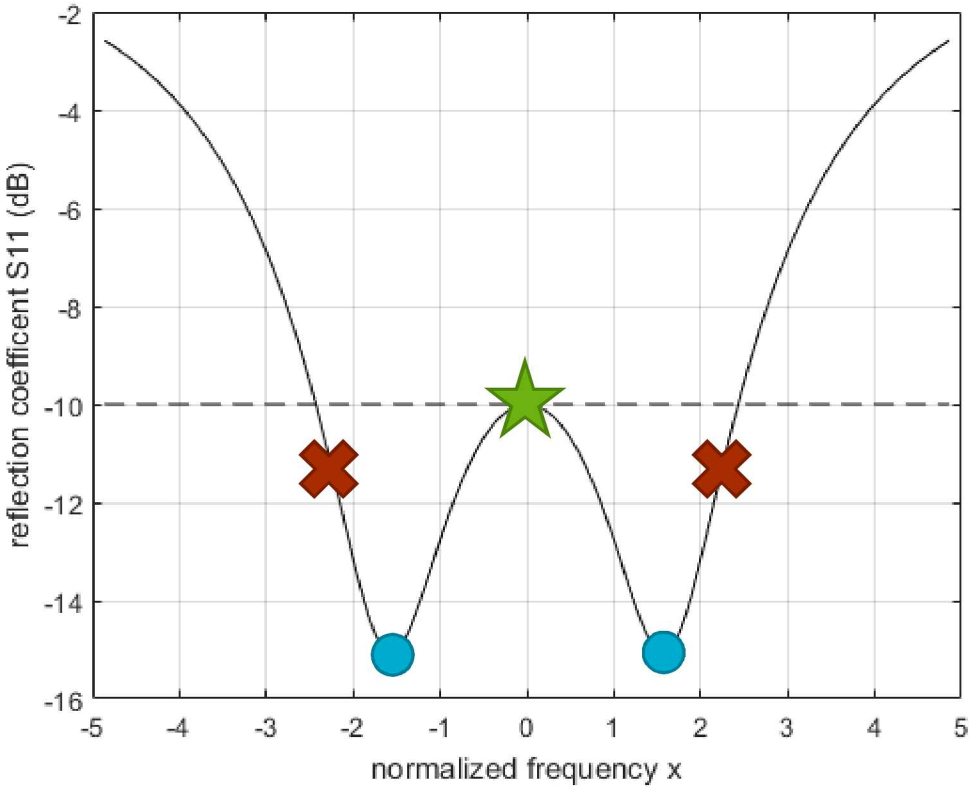
Combine patch and slot resonators into single structure, simulate & refine

$$\frac{BW}{f_0} \sim \kappa$$

$$\kappa = \frac{{\omega_+}^2 - {\omega_-}^2}{{\omega_+}^2 + {\omega_-}^2}$$

Placing resonances





Designing the uncoupled patch

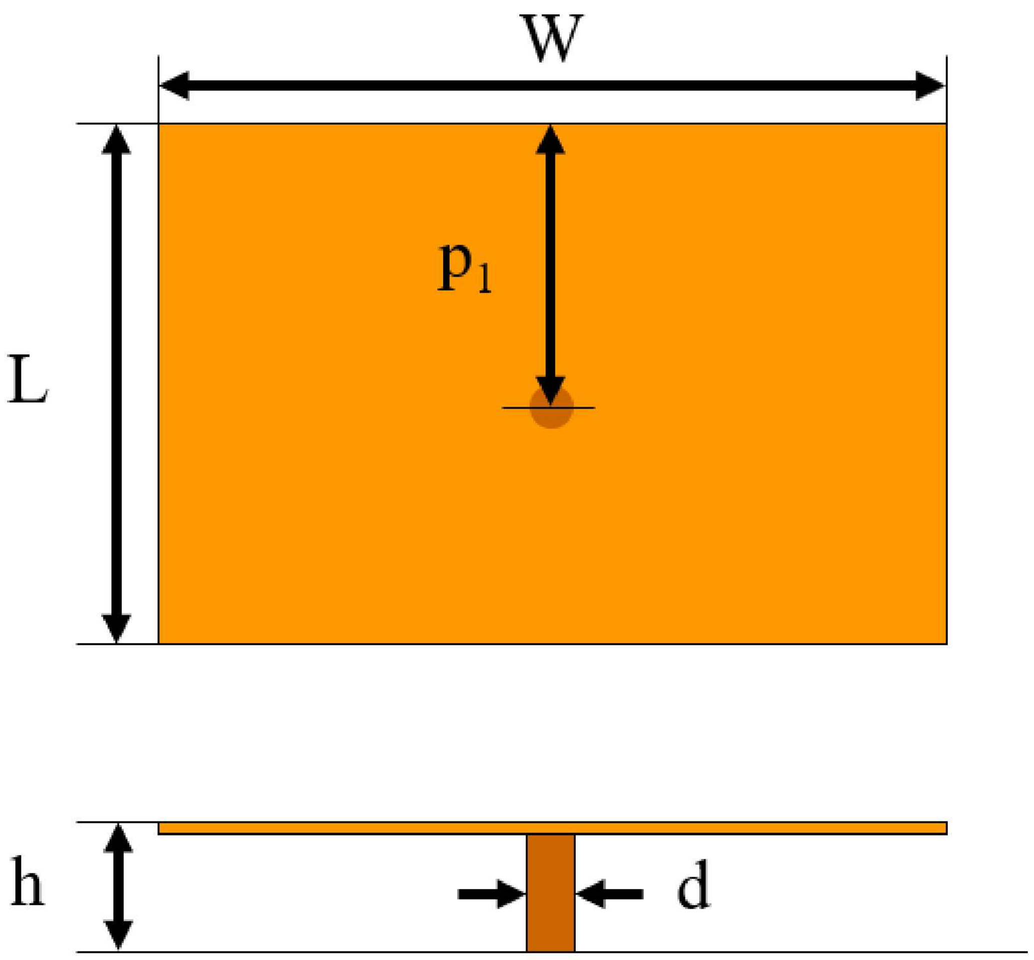
$$Q \sim 2.25 \frac{f_0}{BW} \sim 2.25\,\kappa$$

Minimum Q sets constraints on patch height and substrate Dk

Set L to obtain resonant frequency at band center: $L \sim \lambda/2$

Start with $W \sim L/2$ and $p_1 \sim L/2$

Probe has no effect at this point, resonant conductance is very small

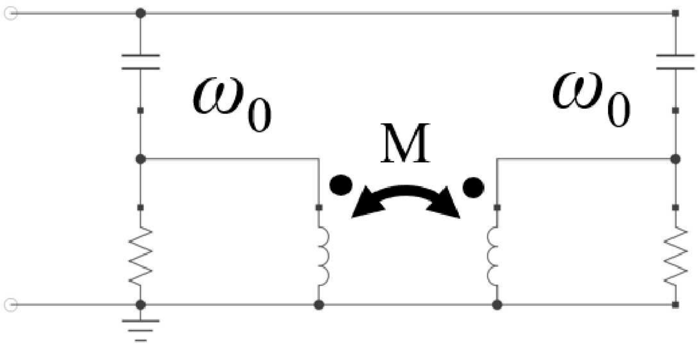


Designing the uncoupled slot

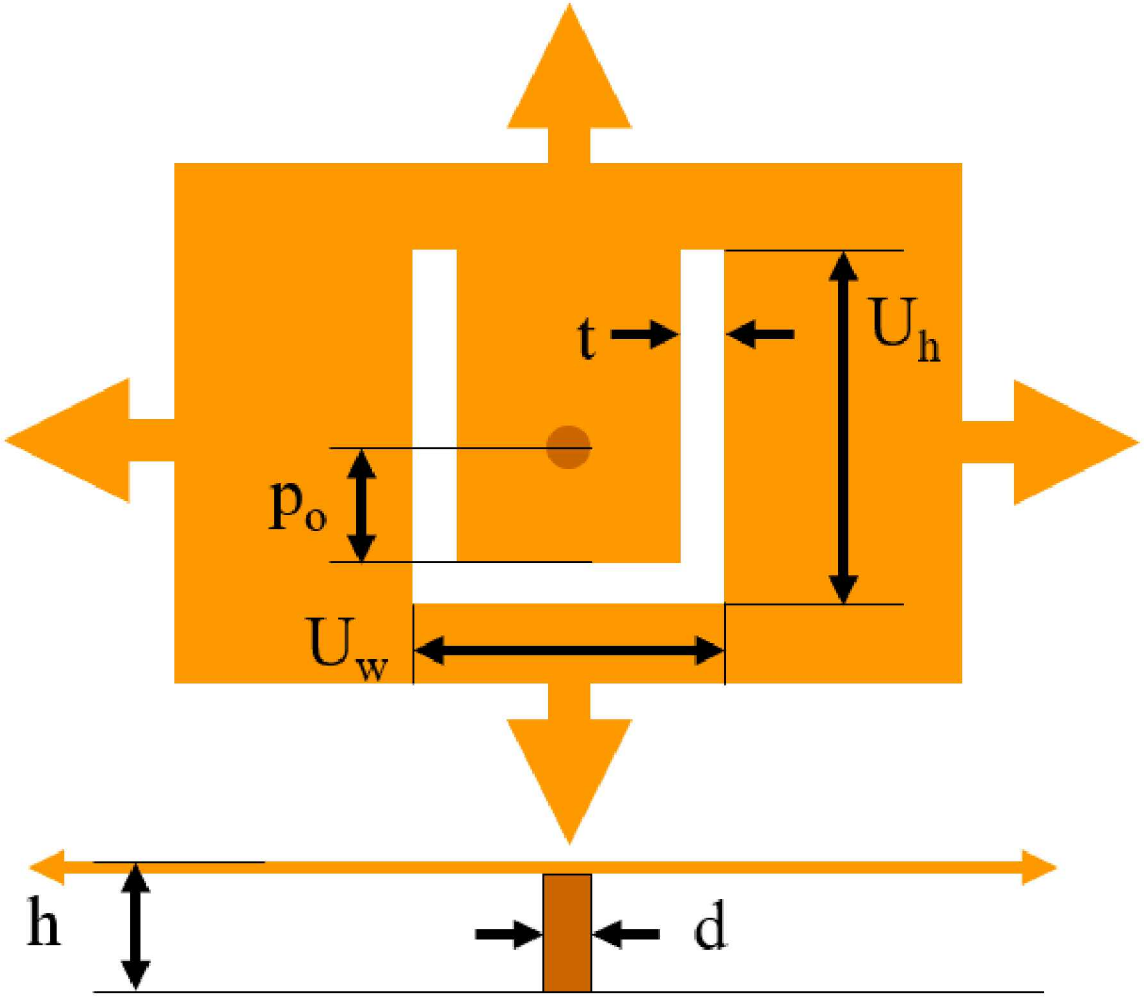
Total length of slot has largest effect on resonant frequency

Start with $U_w \sim \kappa\, W$

Study of the equivalent circuit shows that proper resonant conductance is about 40-50mS.



There are several guidelines to obtaining resonant frequency and conductance; some parameters affect these more than others.

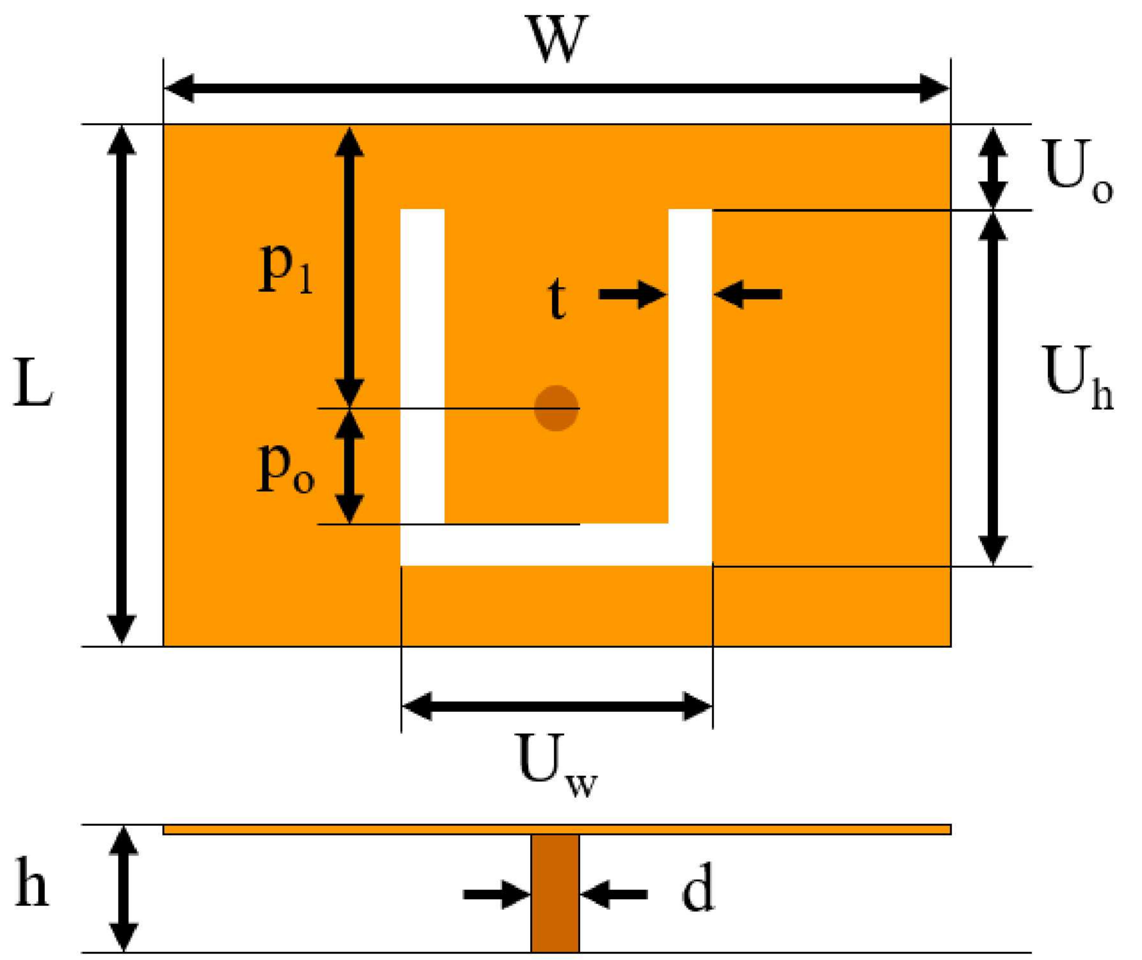


Combine uncoupled resonators & refine

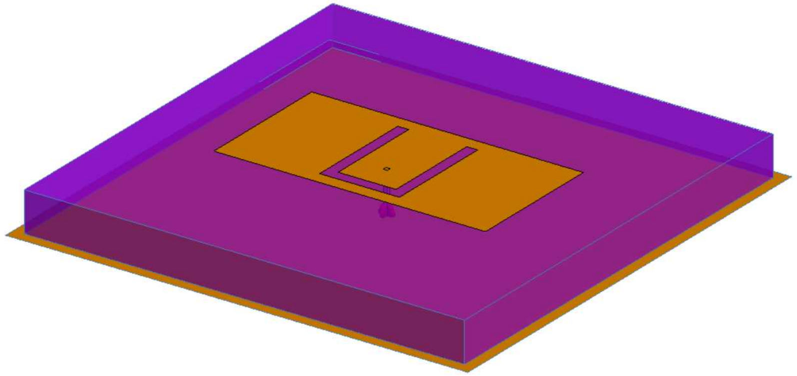
Drop uncoupled U-slot geometry onto patch such that the "U" is centered on the patch; maintain probe offset p_0

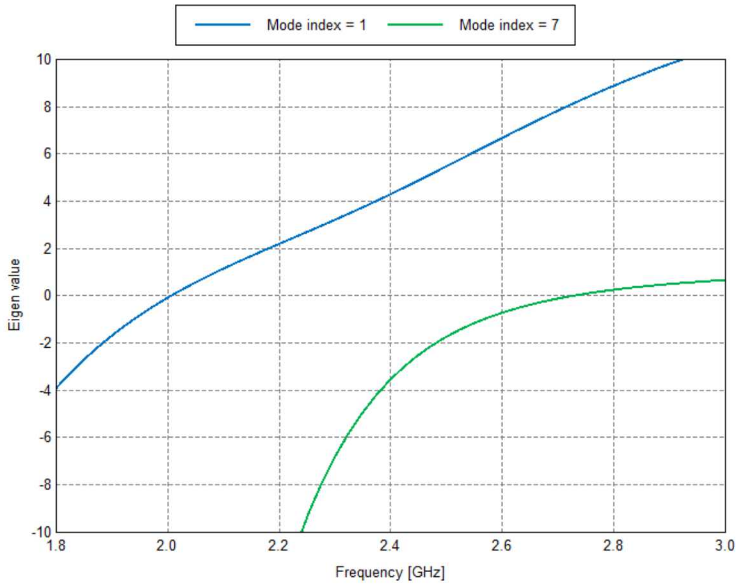
Run driven sim; impedance locus will have a loop in the Smith chart

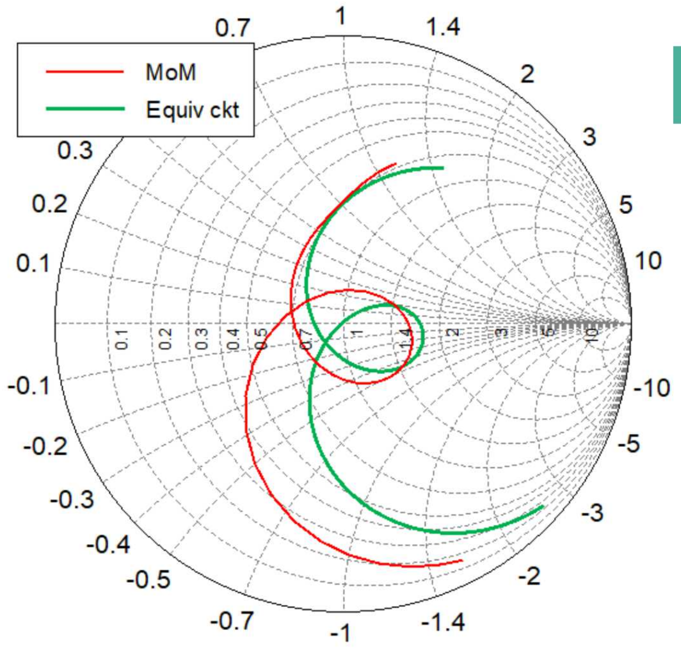
Small adjustments (e.g., to U_0, t, d) can be made such that loop optimally resides within VSWR circle on Smith chart

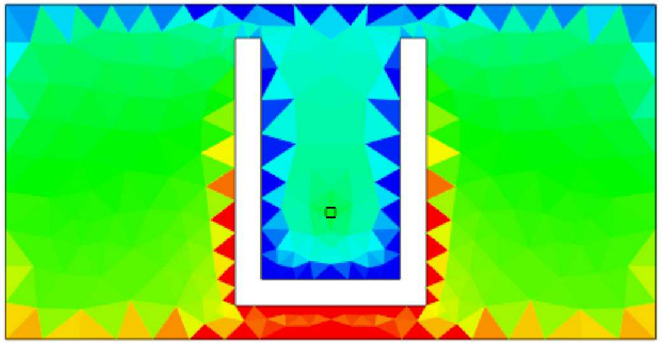


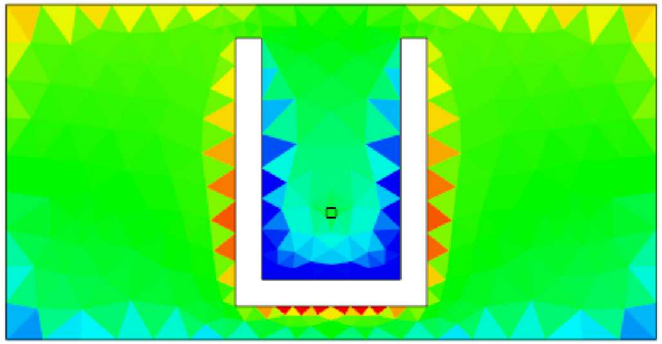
Example design

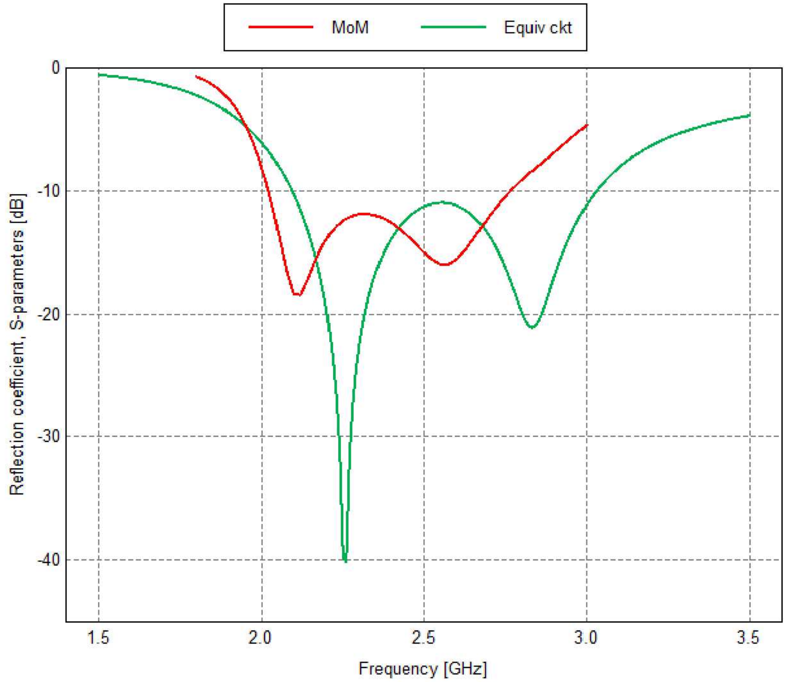












Main Conclusions about the U-slot patch

The U-slot patch operates with **coupled** modes; the patch and slot modes are equally important over the entire impedance bandwidth

The patch provides the majority of the radiation; the slot comparatively less

Due to the probe location, the patch mode is not well matched to 50Ω but the lumped LC "slot" resonator causes a good match

Take-Homes

Coupled mode theory is **everywhere** in electrical engineering

Characteristic mode analysis is a modal decomposition method that can provide insight into EM/antenna designs

After a bit of modal deconstruction, sensible guidelines for designing the U-slot patch antenna can be developed