Electrically Small Spiral Transmission Line-Connected Triple-Arm Folded Monopole Antenna

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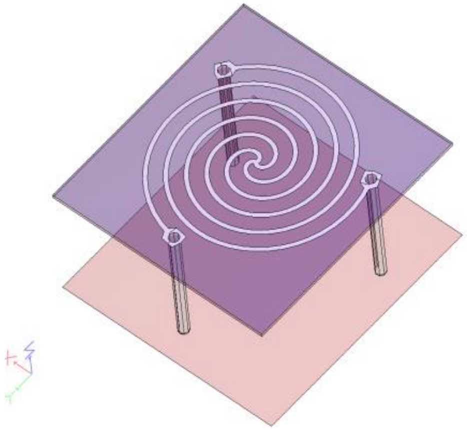

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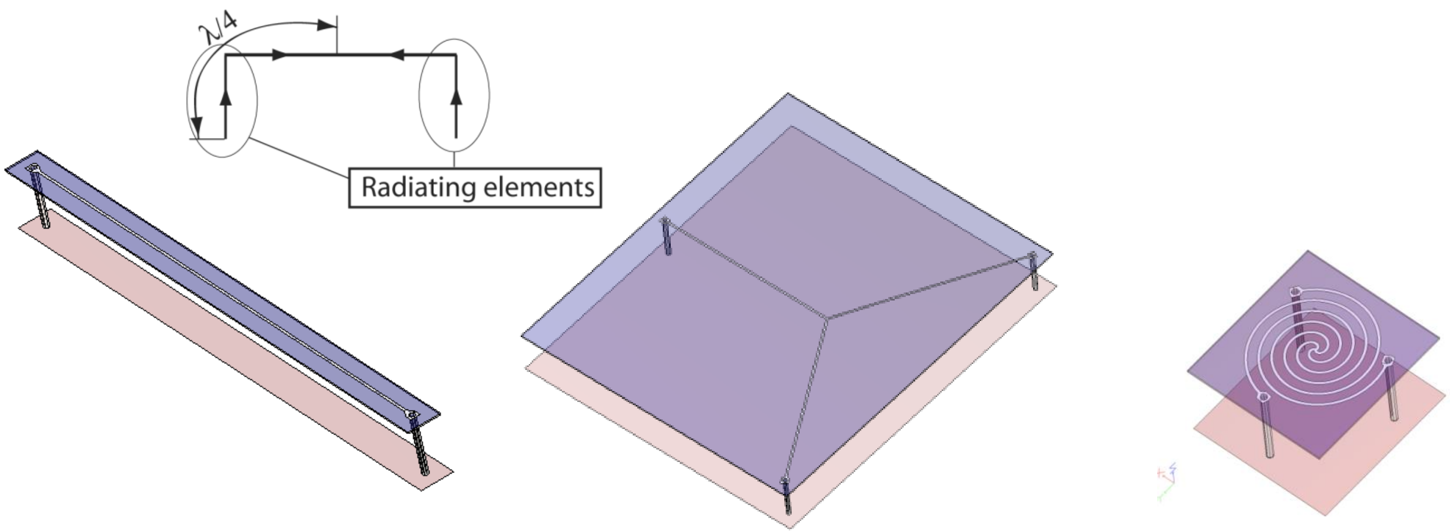
Motivation

Addressing two issues:

- Approaching fundamental bounds with a simple manufacturable geometries (cylinders, cuboids, NOT sphere) of el. small antenna composed of horizontal metallic layers and vias only
- Application of self-resonant short multiple-arm not too closely spaced monopoles ($s > 0.05\ \lambda_0$) - how does it affect Z_{in}?

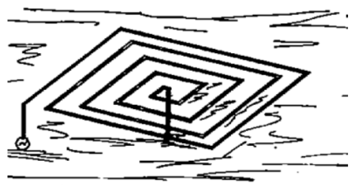


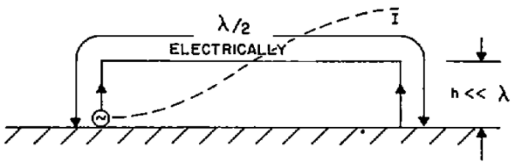
Outline

1. Short multiple-arm monopoles
2. Triple-arm monopole antenna
3. Input impedance/resistance
4. Comparison with fundamental bounds
5. Summary

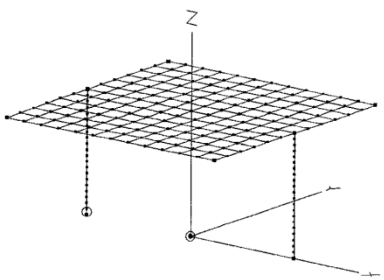
Short multiple-arm monopoles

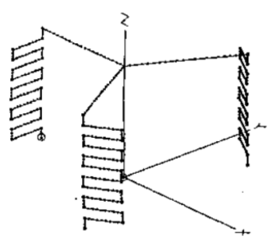
- Dipole/monopole: $R_{rad} \sim c(h/\lambda)^2$, c - depends on the type of current distribution
- Multiple-arms: a technique for increasing radiation resistance, $R_{\text{rad, N dipoles}} \sim N^2 R_{\text{rad, dipole}}$ for dipole spacing $s < 0.05\ \lambda_0$
- In-phase feeding must be ensured between monopoles, possibly by e.g.
    - ~ λ/2 winding[1)]



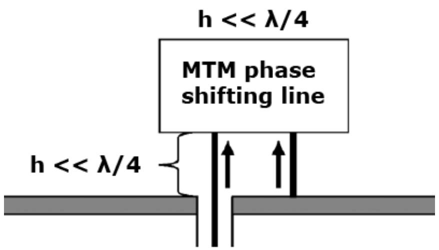


    - reactive (capacitive, inductive) loading [2)]





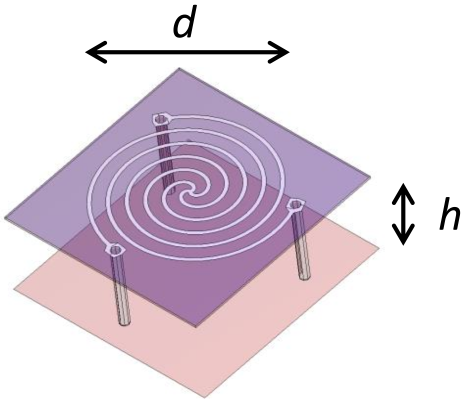
    - MTM cells [3)]

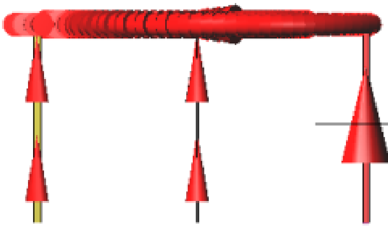


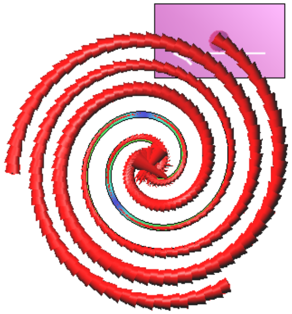
1) Fenwick, R. C., TAP 1965
2) Best, S., APM 2005, ..
3) Antoniades, and Eleftheriades, AWPL 2008, Kokkinos, and Feresidis, TAP 2009, ..

Triple-arm monopole antenna design

- Cylindrical geometry:
  $d = \lambda_0/10$, is $h = \lambda_0/20$, $f_0 = 3.0$ GHz -> $ka = 0.44$
- Spiral TL:
  $r(\varphi) = \alpha\varphi$, $r(\varphi = 4\pi) = \lambda_0/20$ => $\alpha = \lambda_0/(80\pi)$ and $l_{TL}+2h = \lambda_0/2$
  monopole distance $0.05 < s < 0.01\ \lambda_0$
- Winding/spiral TL occupy specific area
- Are dipoles still closely spaced?
  Does spacing larger than $s > 0.05\ \lambda_0$ affect significantly $\sim N^2$?
- How close to fundamental bounds is it?







Input impedance

- Evaluation of Z_{in} of an array of N closely spaced elements by method of induced electromotive forces (EMF) [4, 5]

$$\frac{V}{N} = \sum_{N} I_N Z_{1N} = I_1 Z_{11} + I_2 Z_{12} + I_3 Z_{13}$$

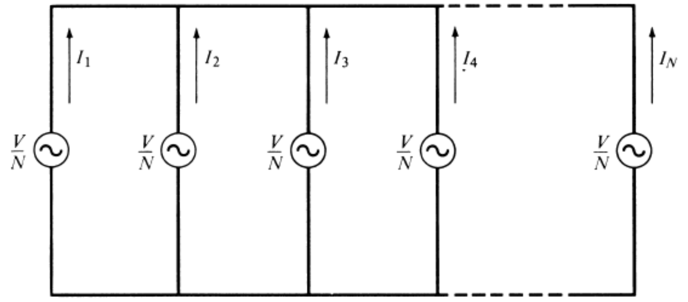
supposing $I_1 \approx I_2 \approx I_3 \approx I$ and $Z_{11} \approx Z_{1N}$ gives

$$Z_{in} = \frac{V}{I} = N^2 Z_{11}$$

If we assume $Z_{11} \neq Z_{1N}$ then we acquire

$$Z_{in} = \frac{V}{I} = N(Z_{11} + Z_{12} + Z_{13})$$

Evaluation of $Z_{1N}\left(s_{pq}\right)$ necessary.



[4] Carter, TAP 1932

[5] Balanis, C., Antenna Theory, Analyzes and Design, 1997

Input impedance

- Mutual impedance of two dipoles [6)]

$$Z_{pq} = \frac{j\eta}{4\pi k} \int_{-h/2}^{h/2} \int_{-h/2}^{h/2} \frac{I_p(z) I_q(z')}{I_p I_q} \left(\partial_z^2 + k^2 \right) G_{pq}(z-z')\, dz dz' \qquad G_{pq}(z-z') = \frac{e^{-jkR_{pq}}}{R_{pq}}, \quad R_{pq} = \sqrt{(z-z')^2 + s_{pq}^2}$$

- Assuming uniform current distribution $I_p = I_q = I$ we get

$$Z_{pq} = \frac{j\eta}{4\pi k} \int_{-h/2}^{h/2} \int_{-h/2}^{h/2} \left(\partial_z^2 + k^2 \right) G_{pq}(z-z')\, dz dz'$$

$$\left(\partial_z^2 + k^2 \right) G_{pq}(z-z') = \frac{(1+jkR)(3(z-z')-R^2) - k^2 R^2 (z-z')^2 + k^2 R^4}{R^5} e^{-jkR}$$

- Using Euler relation $e^{-jkR} = \cos(kR) - j\sin(kR)$ we get for R_{pq}

$$R_{pq} = \frac{\eta}{4\pi k} \iint \left\{ \sin(kR)\left(\frac{3(z-z')^2}{R^5} - \frac{1+k^2(z-z')^2}{R^3} + \frac{k^2}{R}\right) - \cos(kR)\left(\frac{3k(z-z')^2}{R^4} - \frac{k}{R^2}\right) \right\} dz dz'$$

6) Orfanidis, S., Electromagnetic waves and applications, http://www.ece.rutgers.edu/~orfanidi/ewa/

Input resistance

- R_{pq} evaluated numerically for $N = \{2, 3, 4\}$; $s_{pq} > 0.05\ \lambda_0$

  $N = 2$: $s_{12} = 0.1\ \lambda_0$ $\quad Z_{in} = N(Z_{11} + Z_{12})$

  $N = 3$: $s_{12} = s_{13} = \sqrt{3}\lambda_0/20 = 0.087\lambda_0$ $\quad Z_{in} = N(Z_{11} + (N\text{-}1)Z_{12})$

  $N = 4$: $s_{12} = s_{14} = \sqrt{2}\lambda_0/20 = 0.071\lambda_0$, $s_{13} = 0.1\lambda_0$ $\quad Z_{in} = N(Z_{11} + (N\text{-}2)Z_{12} + Z_{13})$

- Monopole, uniform current distribution: $R_{11} = 40(kh)^2$

  $N = 2$: $R_{11} = 3.95\ \Omega$, and $R_{12} = 3.62\ \Omega$

  $N = 3$: $R_{12} = R_{13} = 3.69\ \Omega$

  $N = 4$: and $R_{12} = R_{14} = 3.77\ \Omega$, $R_{13} = 3.62\ \Omega$

- R_{in} of spiral TL-fed multiple-arm monopole antenna - calculated by EMF and compared with EM simulation (MoM IE3D)

Parameters

- R_{in} , radiation efficiency, ~ N^x dependence

N	f_{res} (GHz)	$R_{in,N,sim}$ (Ω)	$R_{in,N,EMF}$ (Ω)	$eff_{r,\ sim}$ (%)	$R_{in,N,sim}/R_{11}$	$R_{in,N,EMF}/R_{11}$	x_{sim}	x_{emf}
2	2.86	16.6	15.1	86.6	4.2	3.8	2.07	1.93
3	3.00	42.7	34.0	88.1	10.8	8.6	2.17	1.96
4	3.05	69.9	60.4	89.7	17.74	15.3	2.07	1.97

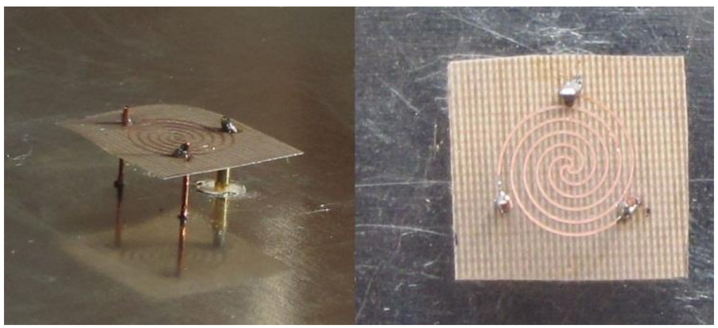
- $R_{in,\ N}$ ~ $N^x R_{in}$ where **x ~ 2** even for **$0.05 < s < 0.1\ \lambda_0$**

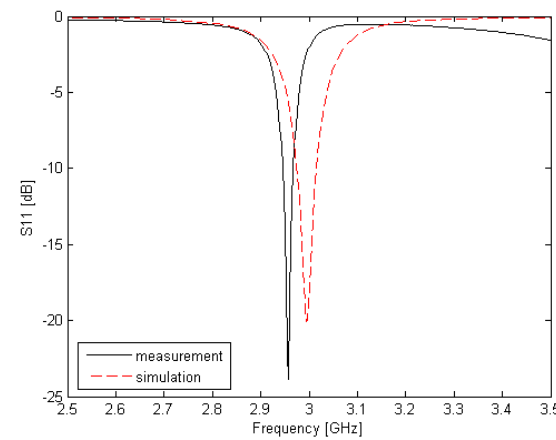
Triple-arm monopole antenna design

- Prototype:

low permittivity substrate Taconic TLP - 3-0050-c1/c1 (ε_r = 2.33, tanδ = 0.0009 @2.5 GHz), height 0.13 mm, suspended above GND at height 4.9 mm

ground plane size 1.4 × 1.4 λ_0

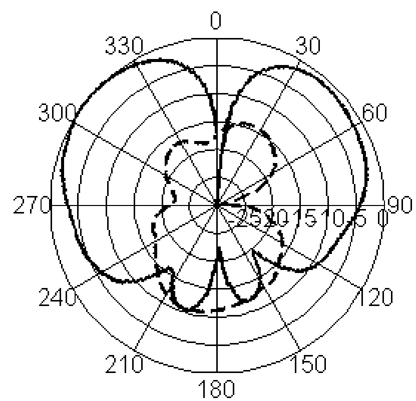




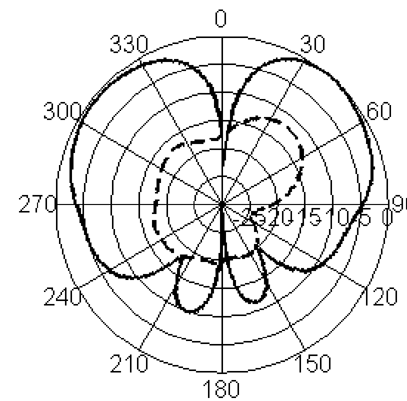
FBW_{meas} = 0.83% (VSWR = 2) @2.96 GHz

$Q_{FBWmeas}$ = 85

	f_{rez} (GHz)	R_{rad} (Ω)	Radiation efficiency (%)
3 Arms - Simulated	3.00	42,7	88,1
3 Arms - Measured	2.96	60,.0	81,7



xz-plane



yz-plane

Comparison with fundamental limitations

- $Q_{Chu} = 1/(ka)+1/(ka)^3$
- $Q_{Thal} = 1/(\sqrt{2}ka)+1.5/(ka)^3$
- $Q_{Gustafsson} = 1.5/((ka)^3\gamma_1^{norm})$ [7], $D = 1.5$, $\eta = 0{,}5$ (absorbtion efficiency), rational approximations for norm. polarizability

$$\frac{\gamma_{cv}(\xi)}{a^3} \approx \xi \frac{6.241 + 59.056\xi + 36.097\xi^2}{1 + 5.2995\xi - 1.92\xi^2 + 7.453\xi^3}$$

- $Q/Q_{Chu} = 7.5$
- $Q/Q_{Thal} = 4.5$
- $Q/Q_{Gustafsson} = 2.2$ (cylindrical geometry, vertical polarization)

[7] Gustafsson, M. et al, TAP 2009, and Technical report TEAT-7195(2010)

Summary

- Short triple-arm self-resonant spiral TL-fed monopole antenna proposed
- Simple manufacturable geometry
- Cylindrical geometry with aspect ratio h/d = 1/2 (incl. mirror currents h/d = 1)
- $R_{\mathrm{rad,\,N}} \sim N^{x} R_{\mathrm{rad}}$ where x ~ 1.96 for $0.05 < s < 0.1\,\lambda_0$
- $Q/Q_{\mathrm{Gustafsson}} = 2.2$

Thank you for attention

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