Designing Oscillator for an Antenna at $\sim 3.5[GHz]$

2896

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Edoh Shaulov

Tel Aviv University

Milestones completed so far

List of Milestones completed

- Selected the transistor we will use
- Simulated the oscillator we designed in PSpice
- Designed Matching network for the load(antenna)
- Optimised matching network for efficiency
- Designed Antenna

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Choosing the BJT

Reqired characteristics

- The transistor needs high-frequency performance, including $f_{\max}$ and f_t, well above $3.5[GHz]$.
- Low parasitic capacitance at collector, base, and emitter terminals is crucial.
- Low noise figure is essential.
- High gain, especially at the operating frequency, is necessary for stable oscillation.
- Ensure appropriate biasing for Colpitts oscillator operation, including DC voltages and currents.

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Transistor Details

BFP520 from Infenion[1]

- Surface mount low voltage silicon NPN RF bipolar transistor
- Transition frequency f_T of $45[GHz]$
- High Gain, with $|S_{12}|, G_{ma}, G_{ms} > 16[dB]$ at $3.5[GHz]$ under $V_{ce} = 2[V]$
- Low Noise Figure, $NF < 1.2[dB]$ at $3.5[GHz], 2[V], 2[mA]$

[1] https://www.infineon.com/dgdl/Infineon-BFP520-DS-v02_00-EN.pdf?fileId=5546d462689a790c01690f035fe2391a

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Oscillator Circuit

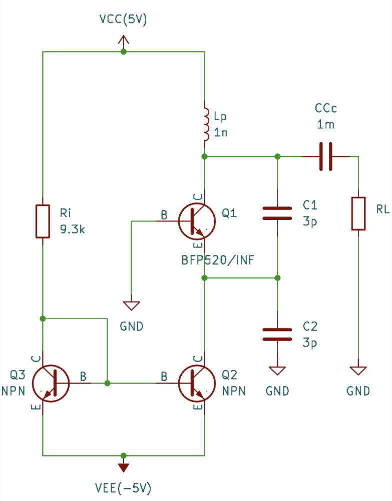
Collpit's Oscillator

- The circuit was tested with some high impedance load attached
- Values of L_p, C_1 and C_2 were computed using the operating frequency formula

$$f_c \approx \frac{1}{2\pi\sqrt{L_p \frac{C_1 C_2}{C_1 + C_2}}}$$

[a]

- $C_1 = C_2$ was chosen since it gave the highest oscillation frequency



[a] In-depth analysis in Appendix

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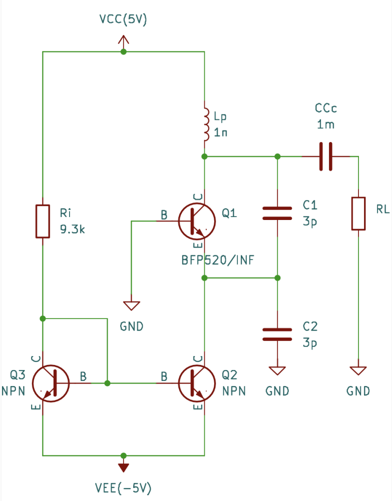

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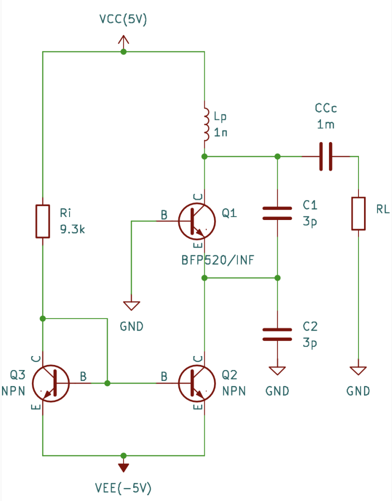

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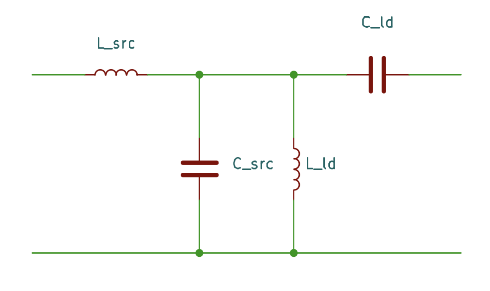
Choosing a Matching Network

Matching Network

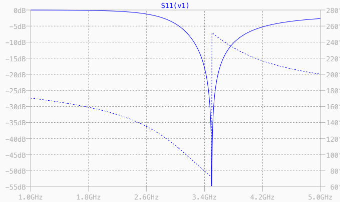
For oscillation to function, we need at-least $R_L \approx 1[k\Omega]$. Thus, we need to match $50[\Omega] \to 1[k\Omega]$ at $3.5[GHz]$. T-matching is better for matching a load to a source impedance when there's a large disparity because it provides efficient power transfer, minimizes losses, and offers impedance transformation with stability.[2]

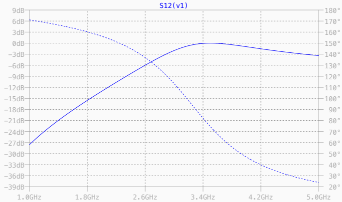
- $L_{src} = 2.03361[nH]$
- $C_{src} = 2.02955[fF]$
- $L_{ld} = 10.4421[nH]$
- $C_{ld} = 0.208424[pF]$

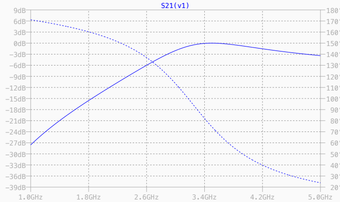


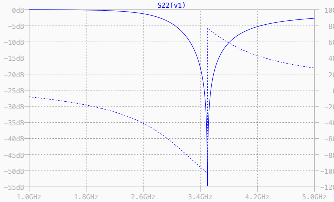
[2]Design method in Appendix

S-parameters of the Matching Network[3]





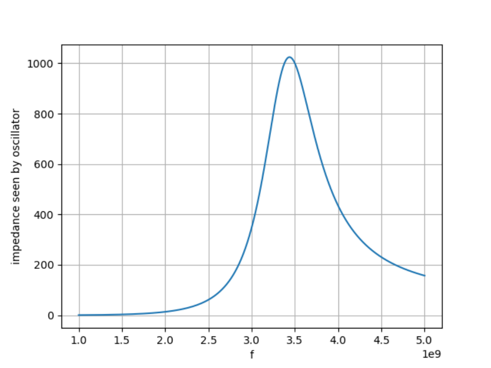




[3] Simulated using .net parameter in LTSpice

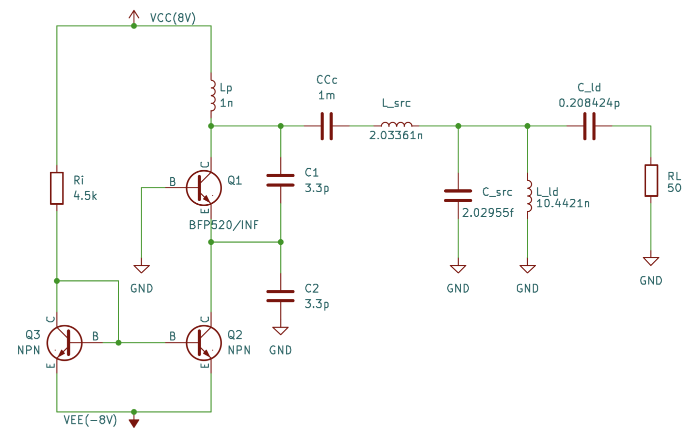
Input impedance through the Matching Network

- Attains max value of $\approx 1000[\Omega]$ at $3.5[GHz]$
- Tapers quickly for the non-central frequencies



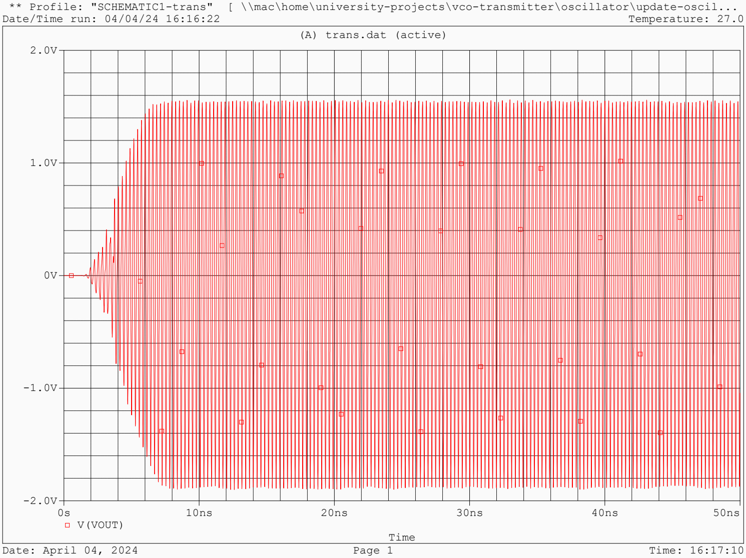
Oscillator Simulation

After making adjustments to supply and current to maximize efficiency, we have the following system[4]

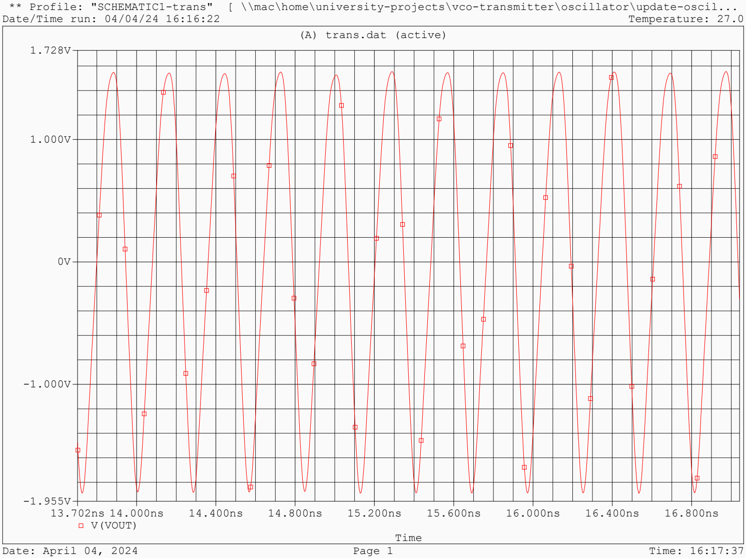


[4]Efficiency η is defined in the next section

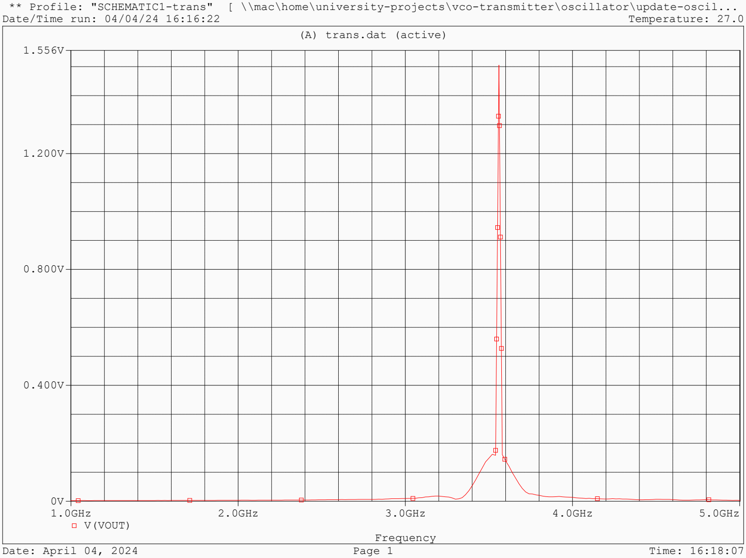
Output of Oscillator - Transient



Output of Oscillator - Transient Zoomed



Output of Oscillator - Fast Fourier Transform



Efficiency

Calculation of η

- **Input:** $P_{DC} = V_{CC} I_C$
- **Output:** $P_{ac} = \frac{V_{rms}^2}{R_L}$ where $V_{rms} = \frac{V_{max}}{\sqrt{2}}$ for the output waveform
- **Efficiency:** $\eta = \frac{P_{ac}}{P_{CD}}$

[5] It has been shown (Krauss, et al., 1980) that the maximum theoretical efficiency for this oscillator configuration is 25%, implying we have a decent efficiency

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For $V_{cc} = -V_{ee} = 8[V]$, and current mirror set to give $3.36[mA]$, we have $v_p = 1.6[V]$, giving us

$$\eta \approx 20\%^5$$

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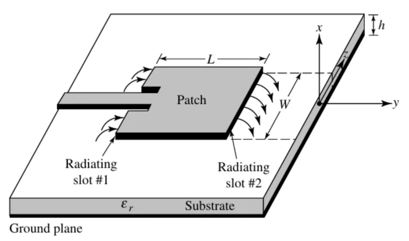
Antenna Design

- Microstrip patch antenna with an inline microstrip line feed
- Input impedance of 50[Ω]
- Directional Antenna with good efficiency and high gain when used in an antenna array



Antenna Decisions

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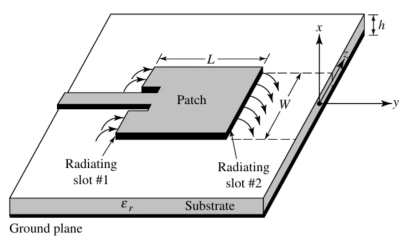

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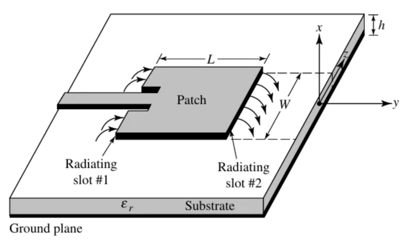


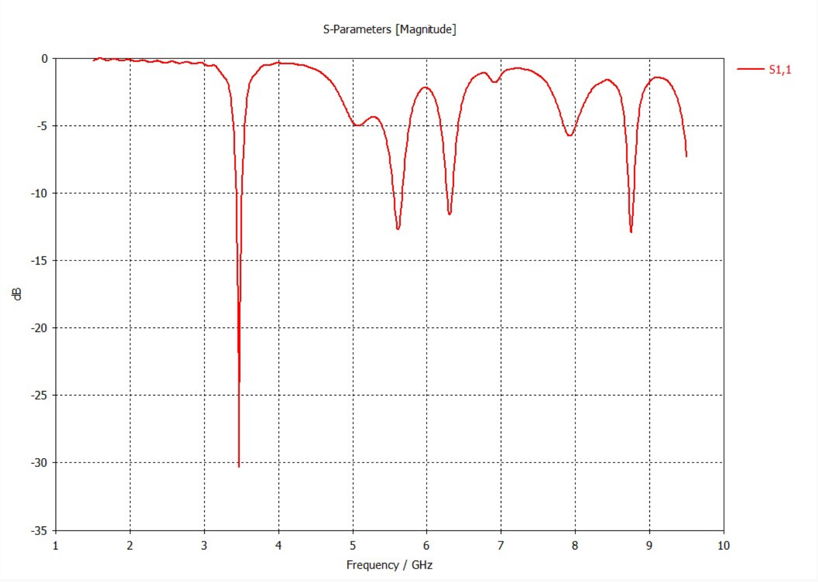
Single Patch Antenna

The following antenna was used, with Rogers substrate[6]

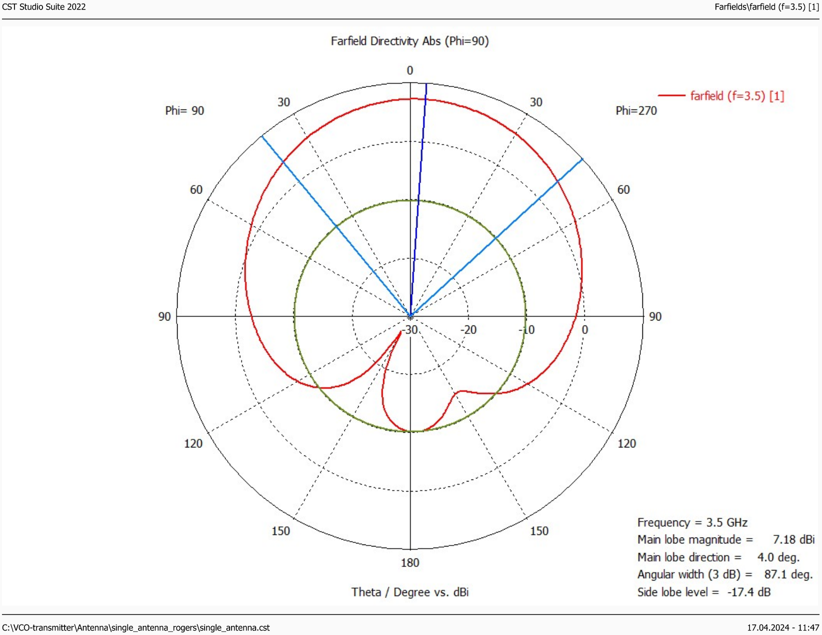
Parameter	**Value[mm]**
H	1.52
W	28.08
L	21.69
y_0	7.89
W_{gnd}	51.65
L_{gnd}	45.26
W_{feed}	4.70

[6] All the measurements are in accordance with JLCPCB guidelines - `https://jlcpcb.com/capabilities/pcb-capabilities`

Single Patch Antenna Simulation - S parameters



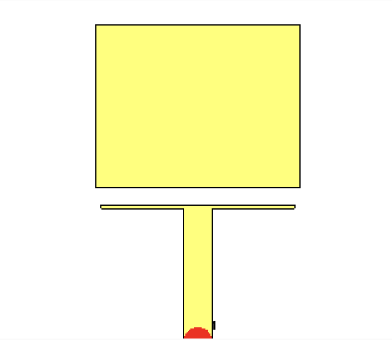
Single Patch Antenna Simulation - Far-field



Wideband Patch Antenna (Ongoing)

The patch antenna designed above cannot provide us the required bandwidth. Thus, the following antenna design used[**?**]

- Extra quarter wavelength resonators for dual resonant frequencies
- If the resonances are close enough, they can be combined to give a larger bandwidth
- Suppression of extra harmonics



Wideband Patch Antenna Simulation - S parameters

Wideband Patch Antenna Simulation - Far-field

Next Steps

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- Look further into the bandwidth of the antenna
- Layout the PCB using Altium
- Fabrication and Testing

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Appendix

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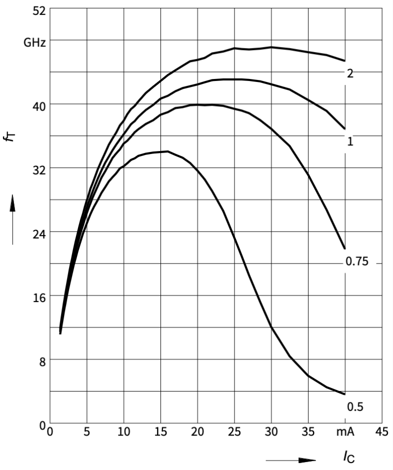
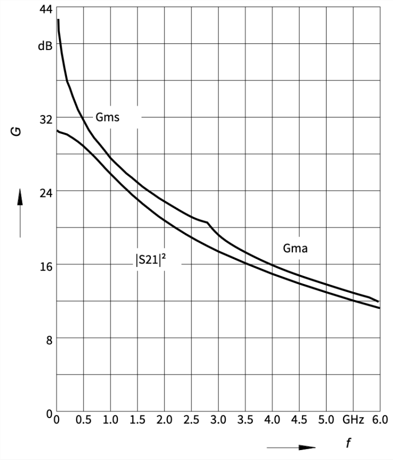
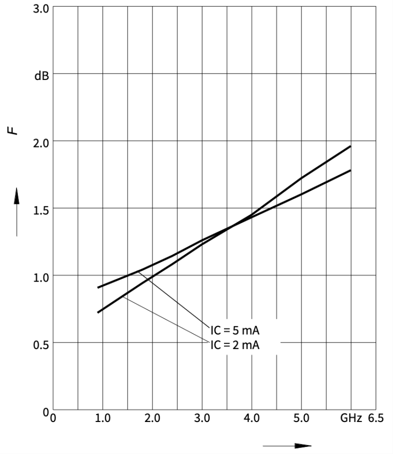
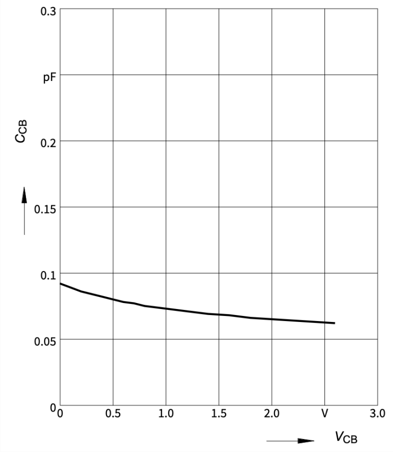




Data from Infenion - 2



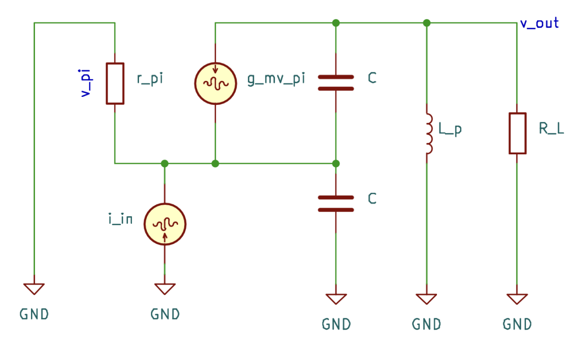


BFP520 Spice File

```
.SUBCKT BFP520/INF 200 100 300
L1      1     10      0.47nH
L2      2     20      0.56nH
L3      3     30      0.23nH
C1     10     20      6.9fF
C2     20     30      134fF
C3     30     10      136fF
L4     10    100      0.53nH
L5     20    200      0.58nH
L6     30    300      0.05nH
Q1     2  1  3  BFP520
.ENDS
.MODEL BFP520 NPN(
+ IS  =1.5E-17      NF =1           NR =1
+ ISE=2.5E-14       NE =2           ISC=2E-14
+ NC =2             BF =235         BR =1.5
+ VAF=25            VAR=2           IKF=0.4
+ IKR=0.01          RB =11          RBM=7.5
+ RE =0.6           RC =7.6         CJE=2.35E-13
+ VJE=0.958         MJE=0.335       CJC=9.3E-14
+ VJC=0.661         MJC=0.236       CJS=0
+ VJS=0.75          MJS=0.333       FC=0.5
+ XCJC=1            TF=1.7E-12      TR=5E-08
+ XTF=10            ITF=0.7         VTF=5
+ PTF=50            XTB=-0.25       XTI=0.035
+ EG=1.11)
```

Proof of operating frequency - 1

We have the following small signal model of Collpit's oscillator, with $C_1 = C_2 = C$[7]



[7] In all the results, we try to ignore effects of r_π and then adjust the values accordingly to get required response

Proof of operating frequency - 2

$$i_{in} = -\frac{v_\pi}{r_\pi} - sC(v_{out} + 2v_\pi)$$

$$g_m v_\pi + sC(v_{out} + v_\pi) + \frac{v_{out}}{sL_p} + \frac{v_{out}}{R_L} = 0$$

This gives us the following frequency response

$$\frac{v_{out}}{i_{in}} = \frac{r_\pi L_p R_L(s^2 C + sg_m)}{r_\pi C^2 L_p R_L s^3 + (-r\pi C L_p R_L g_m + 2r_\pi C L_p + C L_p R_L)s^2 + (2r_\pi C R_L + L_p)s + R_L}$$

Put $s = j\omega$ and let Im of denominator $\to 0$

$$\omega_0 = \sqrt{\frac{2r_\pi C R_L + L_p}{r_\pi C^2 L_p R_L}}$$

Assuming $r_\pi \to \infty$, as is the case is MOS, we reach the well-known expression $\omega_0 = \sqrt{\frac{1}{L\frac{C.C}{C+C}}}$

Proof of operating frequency - 3

For sustained oscillations, we need

$$-(-r_\pi C L_p R_L g_m + 2 r_\pi C L_p + C L_p R_L)\omega_0^2 + R_L > 0$$

This gives us

$$^{8} R_L g_m - \frac{R_L}{r_\pi} - 2 > 0$$

Thus, we need to set R_L accordingly at the oscillating frequency, giving us a lower bound for load and thus a need for a matching network

[8] This is similar to the condition found in Razavi, but for NMOS in place of NPN BJT

Calculation of matching network - 1

We assume a central impedance Z_c such that $Z_c > \max(Z_s, Z_L)$, and then calculate the series and parallel reactive components on both sides.[9]

Source:

$$Q_{src} = \sqrt{\frac{Z_c}{Z_s} - 1}$$

$$X_{src}^{patallel} = \frac{Z_c}{Q_{src}}$$

$$X_{src}^{series} = Q_{src} Z_s$$

Load:

$$Q_{ld} = \sqrt{\frac{Z_c}{Z_L} - 1}$$

$$X_{ld}^{patallel} = \frac{Z_c}{Q_{ld}}$$

$$X_{ls}^{series} = Q_{ls} Z_L$$

Then, $L = \frac{X}{2\pi f_0}$ and $C = \frac{1}{2\pi f_0 X}$ for chosen X series/parallel

[9] In our case, all impedances are real

Calculation of matching network - 2[10]

After this, the values of V_{cc}, V_{ee}, and I_c were changed so as to get the maximum efficiency. R_L was matched to $1[K\Omega]$.

Variable	Value
f_0	3.5×10^9
$Z_{\text{out\_osc}}$	1000
Z_{load}	50
Z_{center}	1002
Q_{src}	0.0447214
$X_{\text{paralle\_src}}$	22405.4
$X_{\text{series\_src}}$	44.7214
L_{src}	2.03361×10^{-9}

Variable	Value
C_{src}	2.02955×10^{-15}
Q_{ld}	4.36348
$X_{\text{paralle\_ld}}$	229.633
$X_{\text{series\_ld}}$	218.174
L_{ld}	1.04421×10^{-8}
C_{ld}	2.08424×10^{-13}
C_{com}	2.10454×10^{-13}
L_{com}	1.70212×10^{-9}

[10] Values generated using Python script

Parameters of a Microstrip line for required Z_0 [?]

For $\frac{W}{d} \geq 1$, we have

$$Z_0 = \frac{120\pi}{\sqrt{\epsilon_{eff}}} \frac{1}{\sqrt{\frac{W}{d} + 1.393 + 0.667 \ln\left(\frac{W}{d} + 1.444\right)}}$$

Solution:

For $W/d < 2$

$$\frac{W}{d} = \frac{8e^A}{e^{2A} - 2}$$

For $W/d > 2$

$$\frac{W}{d} = \frac{2}{\pi}\left[B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r}\left(ln(B-1) + 0.39 - \frac{0.61}{\epsilon_r}\right)\right]$$

where $A = \frac{Z_0}{60}\sqrt{\frac{\epsilon_r + 1}{2}} + \frac{\epsilon_r - 1}{\epsilon_r + 1}\left(0.23 + \frac{0.11}{\epsilon_r}\right)$ and $B = \frac{377\pi}{2Z_0\sqrt{\epsilon_r}}$

Calculation of patch[11]

We measure the width and ϵ_{eff} of the patch using

$$W = \frac{1}{2f_0\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r + 1}}$$

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{\sqrt{1 + \frac{12h}{W}}}$$

Then, the length is measured as

$$\frac{\Delta L}{h} = 0.412\frac{(\epsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

$$L_{eff} = \frac{c}{2f_0\sqrt{\epsilon_{eff}}}$$

and $L = L_{eff} - 2\Delta L$

[11] All the calculations done using Python scripts

Patch Antenna Dimensions for Inline-Feed - 2

Calculation of Feed-point

We want to match antenna to

$$R_{in} = \frac{1}{2(G_1 \mp G_{12})} \cos^2\left(\frac{\pi}{L} y_0\right)$$

where $I_1 = \int_0^{\pi} \frac{\sin^2\left(\frac{k_0 W}{2}\cos\theta\right)}{\cos^2\theta} \sin^3\theta d\theta$ and $G_1 = \frac{I_1}{120\pi^2}$
$I_{12} = \int_0^{\pi} \frac{\sin^2\left(\frac{k_0 W}{2}\cos\theta\right)}{\cos^e\theta} \sin^3\theta \times \mathcal{J}_0(k_0 L \sin\theta) d\theta$[12] and
$G_{12} = \frac{I_{12}}{120\pi^2}$

[12] $\mathcal{J}_0$ represents Bessel's function of 0 order

Patch Antenna Dimensions for Inline-Feed - 3 and Dimensions for Resonators

Constraints on the dimensions of the ground plane

- $\lambda_{eff} = \frac{c}{f_0}\sqrt{\epsilon_{eff}}$
- $L_{gnd} \geq L + 2 \times \frac{\lambda_{eff}}{4}$
- $W_{gnd} \geq W + 2 \times \frac{\lambda_{eff}}{4}$

Dimension of resonators

The resonators are suppose to be quarter wavelength, $L_r = \frac{\lambda}{4}$, where λ is determined by f and ϵ^r_{eff}[13]

[13] This is effective permittivity for resonator, which is different compared to that of the patch

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