# MM Wave Injection Locked Frequency Dividers

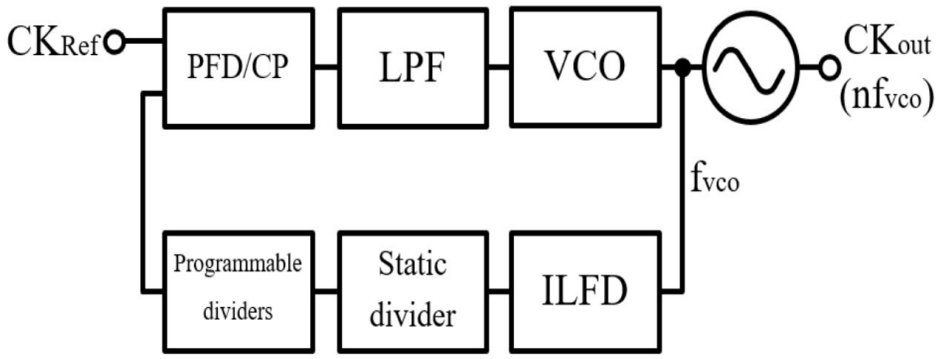

**Justin Heimerl**

SiGe Devices and Circuits

# Who Needs Frequency Division?

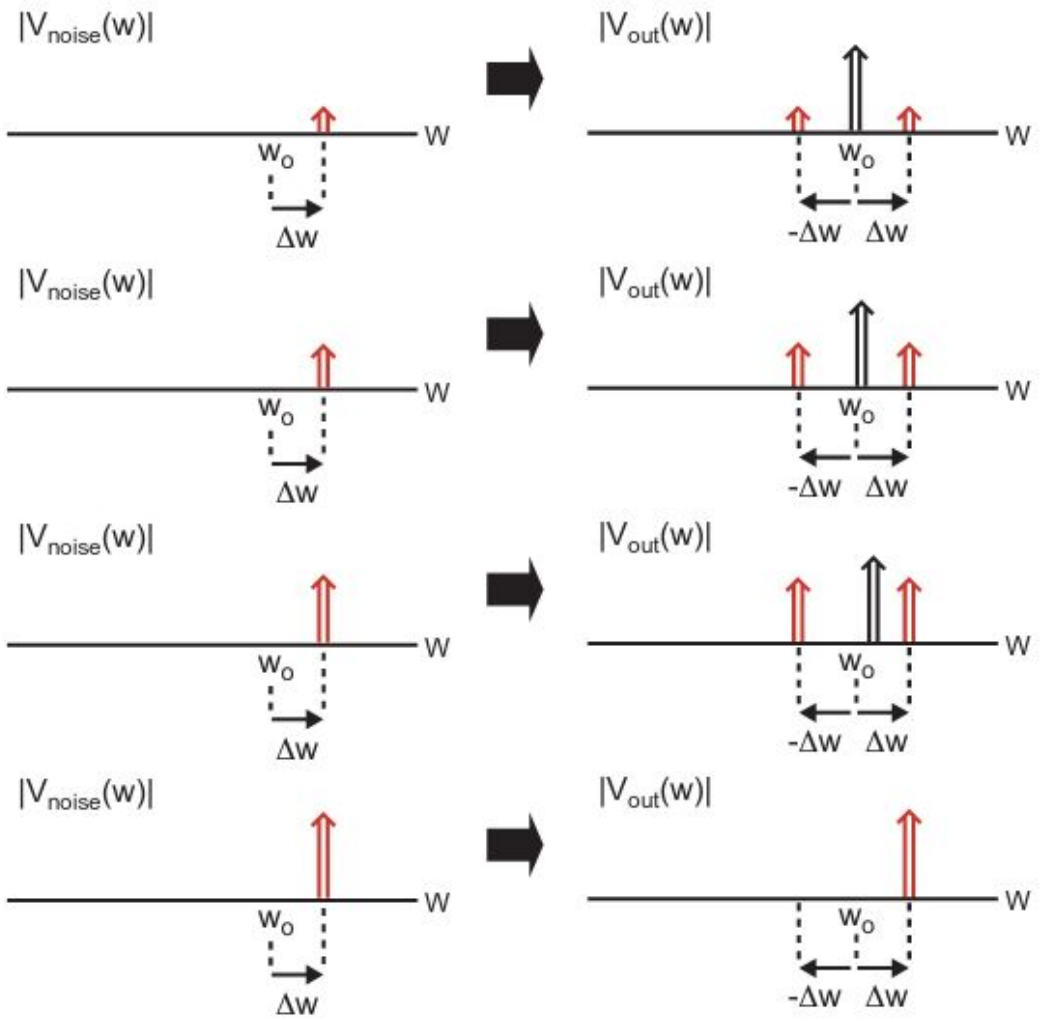
- Any multiplying PLL must use a frequency divider.
- Injection Locked Frequency Divider (ILFD) can be used as first divider.
  - Low DC power consumption.
  - High operation frequency (very viable at mm-wave frequencies).
  - Multiple division ratios.
  - Issue is locking range.

| Divider Technique | Locking Range | DC Power | Operation Frequency | Division Ratio |
|---|---|---|---|---|
| ILFD | Low | Low | High | 2,3, 4, 5 |
| CML Divider | Very High | High | Low | 2^n |
| Miller Divider | High | Medium | Medium - High | 2 |



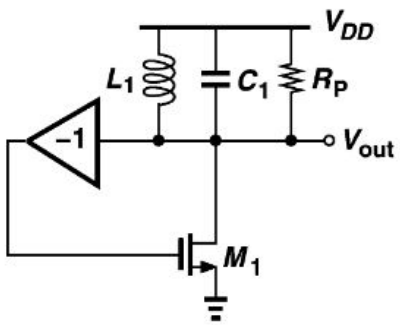
# Basics of Injection Locking

- Discovered in 17th century.
- Phenomenon present in all physical oscillating systems. (electronics, lasers, my cat's vocal cords around other cats)
- If two oscillators are coupled, and close in frequency, they will shift to oscillate at the same frequency.
-

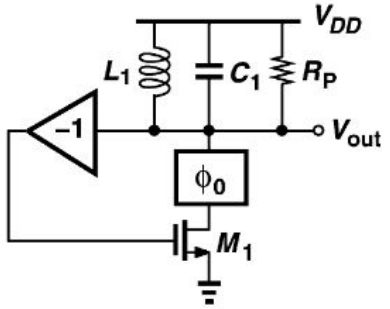


# Injection Locking in Electrical Oscillators

- Consider the LC oscillator in (a).
  - M1 is a CS device, 180° phase shift, inverter for another 180°.
  - What if a signal is injected off resonance?
  - Tank sees this off resonance current, gives a phase shift of $\phi_0$.
  - From Barkhausen criteria, how do we continue oscillating without 360° phase shift?



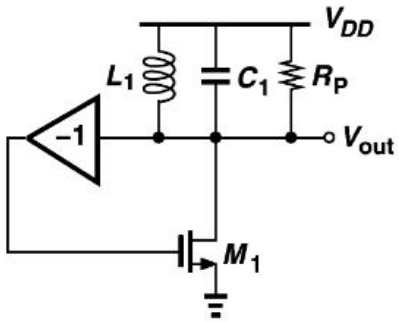
(a)



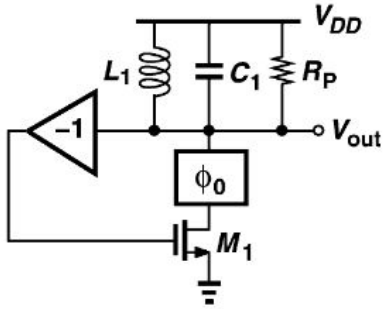
(b)

# Injection Locking in Electrical Oscillators

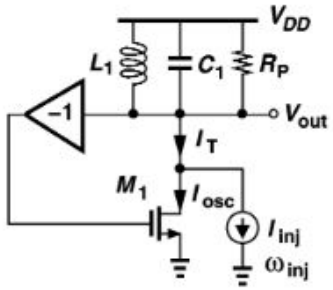
- This phase shift has to be compensated for somehow.
  - The compensation comes from the phase of the current Iosc and Iinj.



(a)



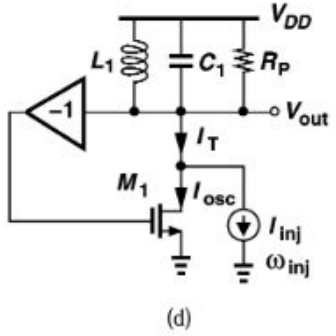
(b)



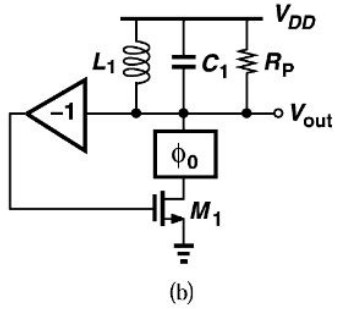
(d)

# Injection Locking in Electrical Oscillators

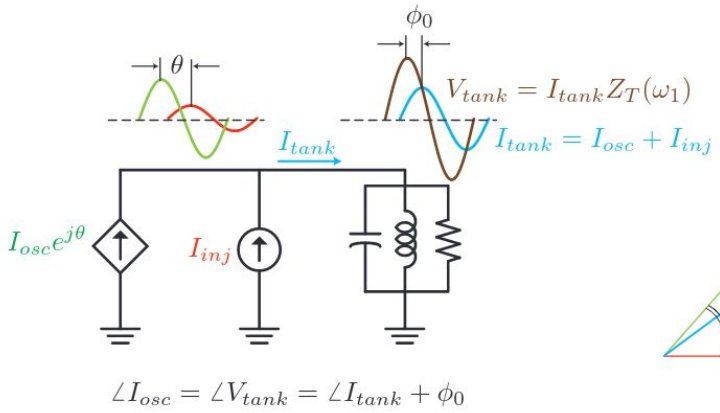
- This phase shift has to be compensated for somehow.
  - The compensation comes from the phase of the current Iosc and Iinj.
  - Iosc is out of phase by $\phi_0$ degrees with Itank. As the injection frequency shifts, this phase difference also shifts.
  - This begs the question of how far can we drift until we can not lock anymore?

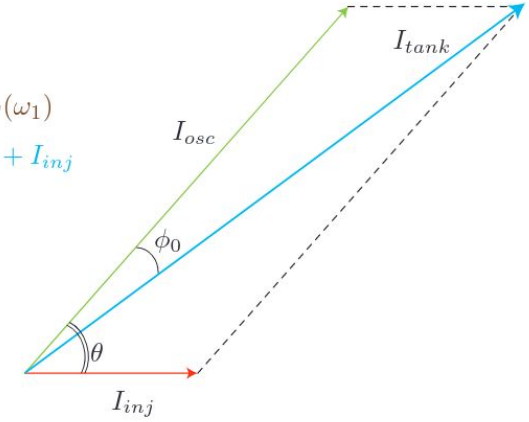


(d)



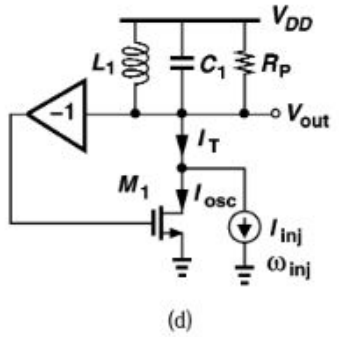
(b)



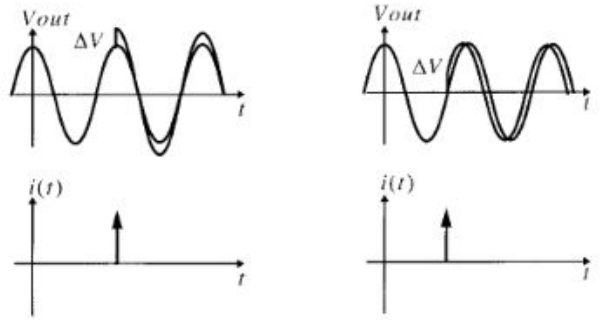



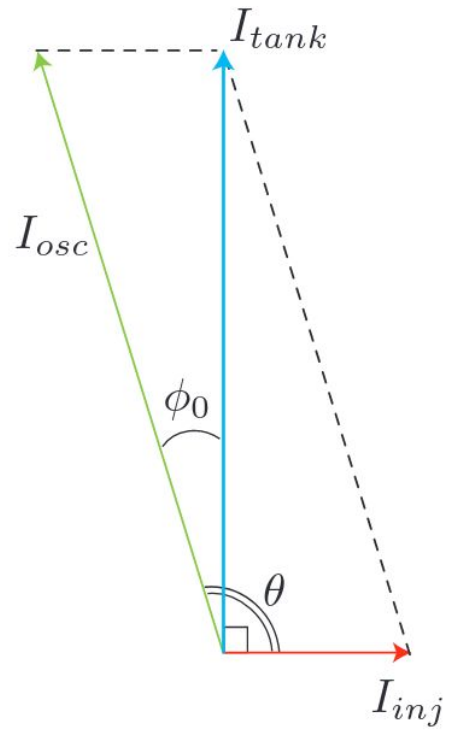
# Injection Locking in Electrical Oscillators

- We can use this information to determine the maximum locking range of the oscillator.
- Tank can only give up to 90° phase shift. When this happens the injected current is being injected at the peak of the tank current, and lock will not occur. (Impossible to produce dϕ/dt if signal is injected at peaks)



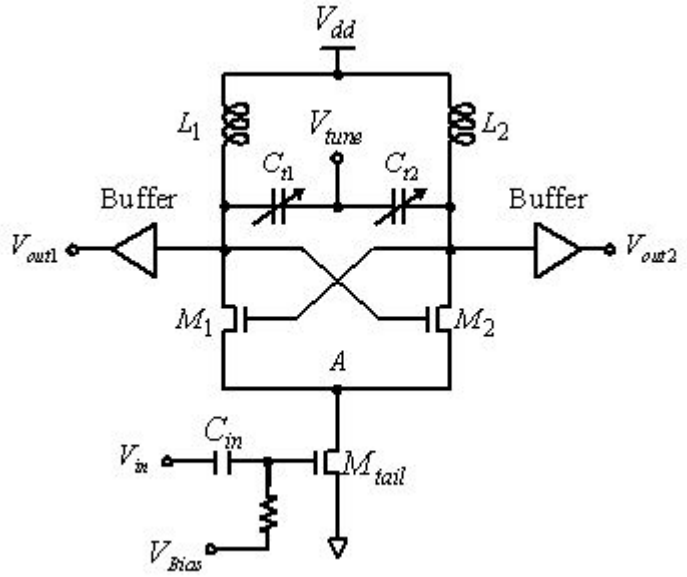
(d)



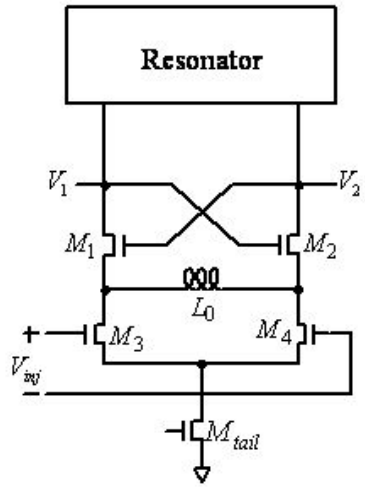
# Basics of Injection Locked Frequency Division

- Basic divide by 2 ILFD is shown.
  - Circuit has a second harmonic signal at node A.
  - Suppose Vin is close to this second harmonic. Node A will lock to Vin. Fundamental will also shift.
  - This accomplishes frequency division for some range of frequencies for which the output signal will lock.
  - Note the use of varactors.



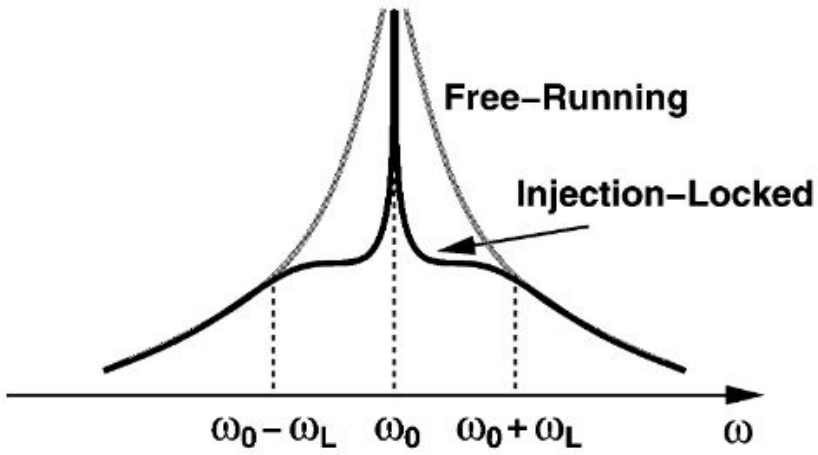
# Basics of Injection Locked Frequency Division

- Basic divide by 3 ILFD is shown.
  - Consider the half circuit of M3, M1, V1.
  - M1 now acts as a mixer, M3 injects current near 3rd (or any odd) harmonic.
  - The X-coupled pair is already oscillating, and thus has a second harmonic at the gate of M1. M1 thus mixes the injection current and 2nd harmonic, allowing one to move the fundamental present at V1.



# But What About Phase Noise?

- Phase noise actually improves compared to free running oscillator.
  - IF the input signal is clean.
  - IF the input signal is within the locking range of the divider.
    - Consider Hajimiri PN model. Where in the period the energy is injected matters.



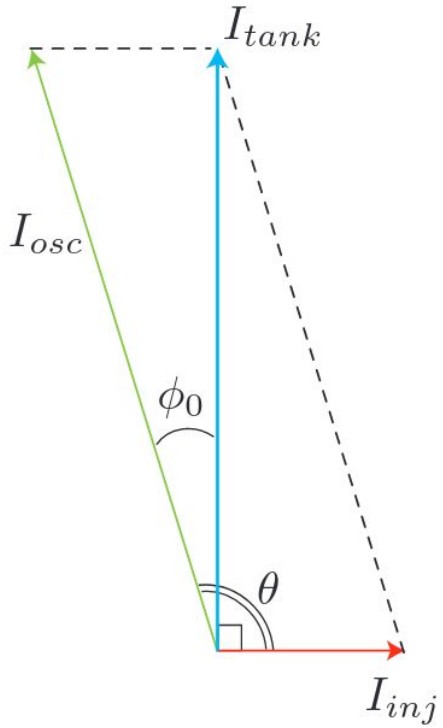

Source: [Razavi]

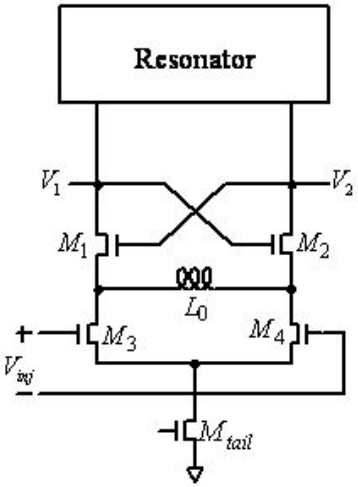
# Problem with Basic Topologies

- The 2nd harmonic here is very weak, resulting a low injection current.
- Increase locking range in 3 ways:
  - Lower Q (bad for phase noise)
  - Decrease oscillation amplitude (also bad for phase noise and output power)
  - Increase injection current (best approach)

$$(\omega_0 - \omega_{inj}) = \frac{\omega_0}{2Q}\frac{I_{inj}}{I_{osc}}\frac{1}{\sqrt{1-\frac{I_{inj}^2}{I_{osc}^2}}}$$

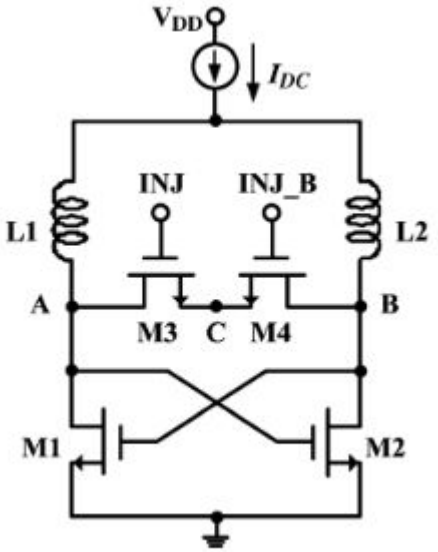
Maximum Locking Range

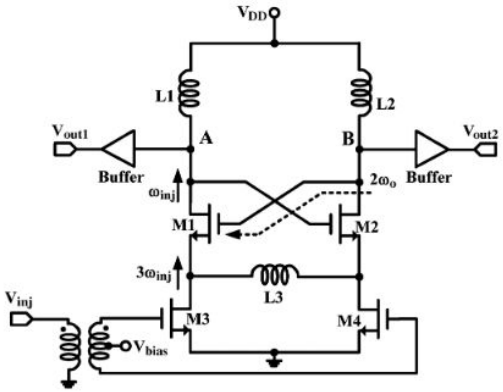


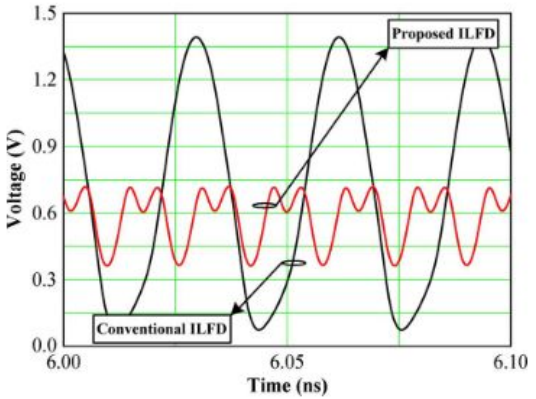



# Isolate Second Harmonic

- Simply floating node C allows for an increase in locking range while paying no power penalty.
- This method can increase 2nd harmonic power by ~8dB.
- Authors also recommend larger device size to de-Q the tank, increase injection current.

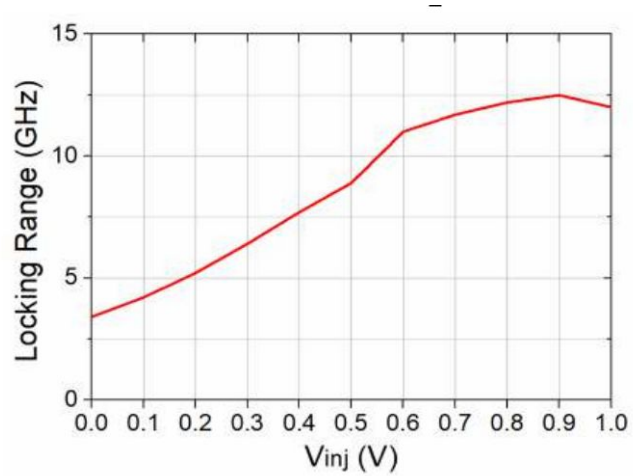


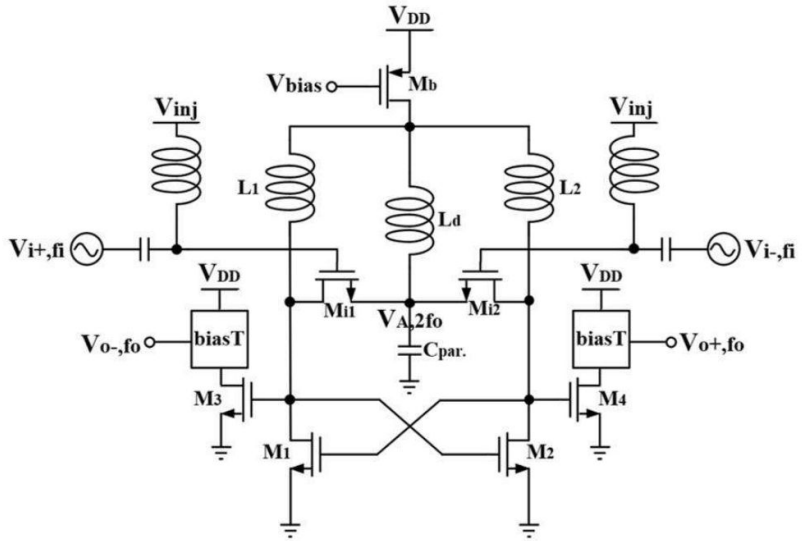



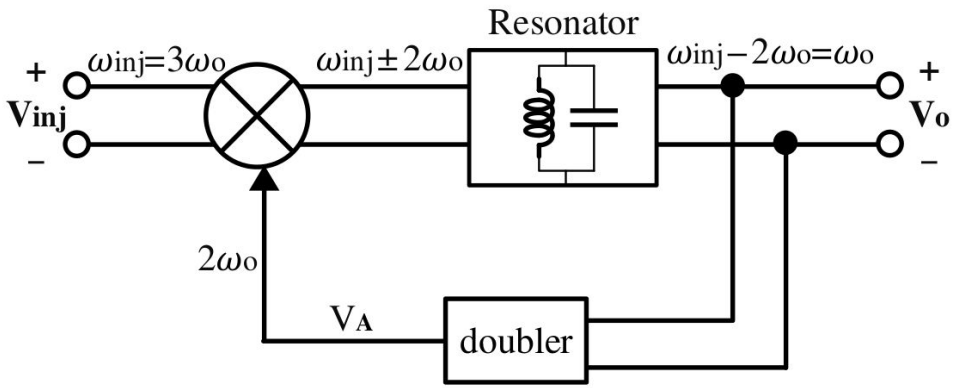



# Second Harmonic Boosting

- Second harmonic amplitude can also be boosted to increase injection current.
  - Simply resonate the second harmonic using Ld, resonates with routing capacitance at 2fo.
  - 14% locking range at 80 GHz

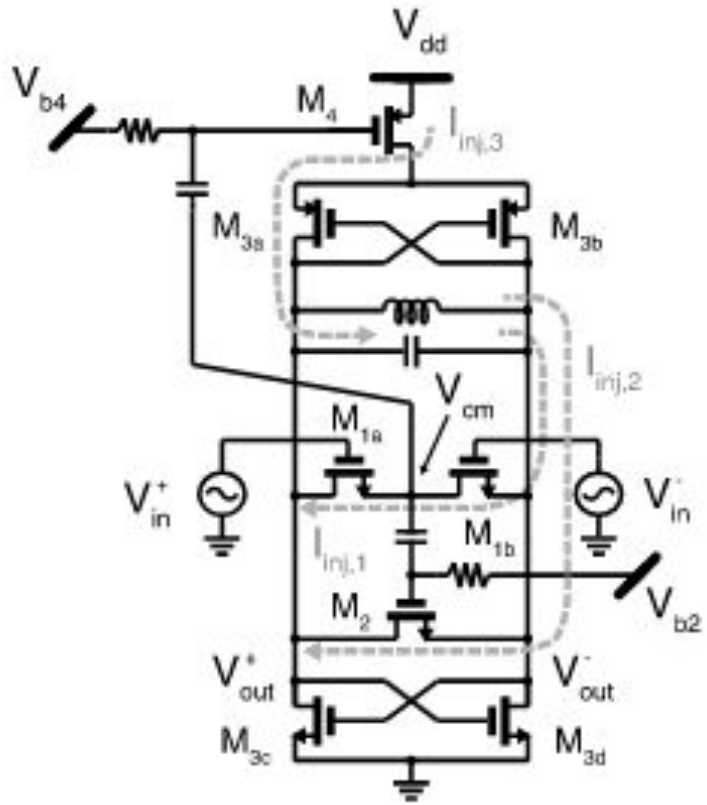


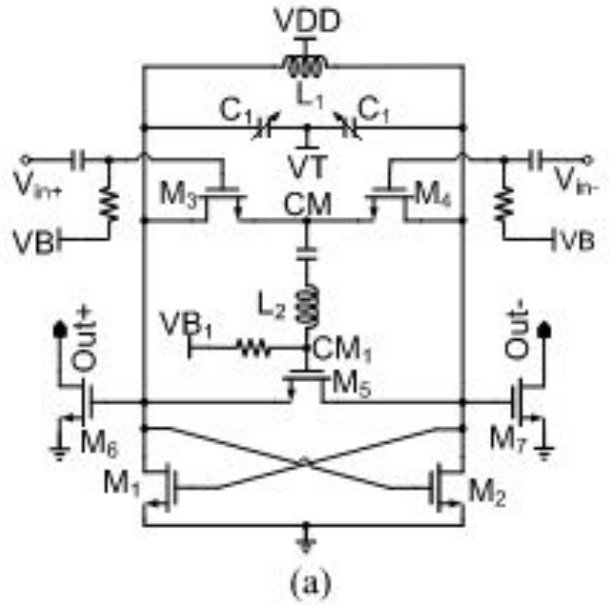
# Second Harmonic Utilization

- Utilizing the second harmonic is the clearest way to increase the injection current, increasing locking range.
- Try to use the second harmonic to boost injection current.
  - Floating the source/drain of the injection devices causes large 2nd harmonic.
  - This harmonic is used as a mixing input into M2, dividing it by 2, increasing the injection current at baseband.
  - 4th harmonic also contributes, but minimally.
  - 23% locking range at 14 GHz



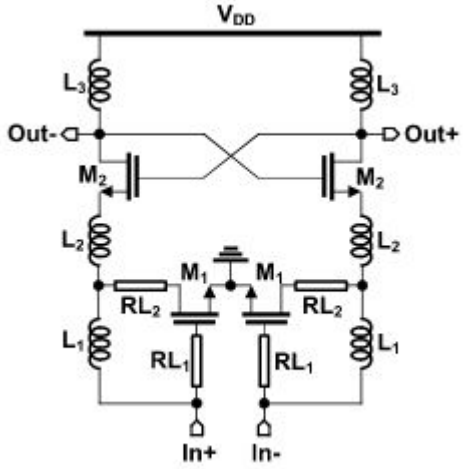
# Why not Both?

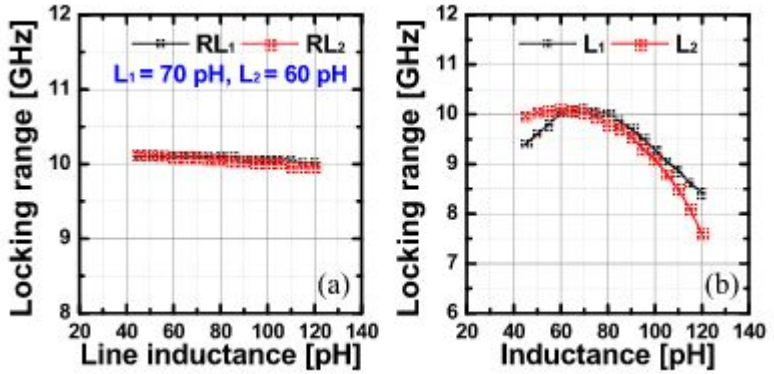
- Resonate second harmonic with routing and device parasitics (using L2 here).
  - CM1 node oscillating at the second harmonic, OUT +/- is at baseband, so mixing occurs.
  - Filter so Iinj is at baseband, boost locking range.
  - ~20% locking range at 30 GHz.



# What about Feedback?

- L1 used to feedback 2 and 3 fo signals, L2 used as peaking inductor.
  - Achieves 10% locking range at W band, uses 7.8mW.
  - Inductor/filter design has a large effect on locking range.
  - Combining this approach with other approaches might have merit. Utilize second harmonic present at output signal and feedback to mixer?



# Conclusions

- Injection locking is a useful idea for frequency synthesis.
- Having access to a divide by three stage is useful in PLL design.
  - If divide by two is sufficient a Miller topology is probably better.
- Most ideas center around utilizing the second harmonic at the common node of the mixers.
- Locking ranges at W band are generally from 10-15% for state of the art.
- Power draw ranges from 1-10 mW for state of the art.
- Lower Q can increase lock range, but you might pay PN penalty.
- Hopefully Sunil isn't shaking his head too hard by this point

# Thank You


1. T. Shibasaki, H. Tamura, K. Kanda, H. Yamaguchi, J. Ogawa and T. Kuroda, "20-GHz Quadrature Injection-Locked LC Dividers With Enhanced Locking Range," in *IEEE Journal of Solid-State Circuits*, vol. 43, no. 3, pp. 610-618, March 2008, doi: 10.1109/JSSC.2007.916590.
2. A. Garghetti, A. L. Lacaita and S. Levantino, "A Low-Power and Wide-Locking-Range Injection-Locked Frequency Divider by Three with Dual-Injection Divide-by-Two Technique," *2018 IEEE International Symposium on Circuits and Systems (ISCAS)*, 2018, pp. 1-4, doi: 10.1109/ISCAS.2018.8350910.
3. Y. Lin and H. Wang, "A 35.7–64.2 GHz low power Miller Divider with Weak Inversion Mixer in 65 nm CMOS," in *IEEE Microwave and Wireless Components Letters*, vol. 26, no. 11, pp. 948-950, Nov. 2016, doi: 10.1109/LMWC.2016.2615013.
4. R. Adler, "A Study of Locking Phenomena in Oscillators" *Proc. IRE*, vol.34, pp. 351-357, June 1946
5. M. Li, H. Kuo, T. Huang and H. Chuang, "60GHz CMOS divide-by-5 injection-locked frequency divider with an open-stub-loaded floating-source injector," *2011 IEEE Radio Frequency Integrated Circuits Symposium*, 2011, pp. 1-4, doi: 10.1109/RFIC.2011.5940608.
6. B. Razavi, "A Study of Injection Locking and Pulling in Oscillators," *IEEE J. Solid-State Circuits*, 39(9):1415-1424, Sept. 2004.
7. Y. Yeh and H. Chang, "Design and Analysis of a *W*-band Divide-by-Three Injection-Locked Frequency Divider Using Second Harmonic Enhancement Technique," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 6, pp. 1617-1625, June 2012, doi: 10.1109/TMTT.2012.2189244.
8. C. Wan, T. Xu and Q. Xue, "A Divide-by-Three ILFD With Second Harmonic Enhancement," in *IEEE Microwave and Wireless Components Letters*, vol. 32, no. 1, pp. 49-51, Jan. 2022, doi: 10.1109/LMWC.2021.3098001.
9. H. Nam and J. Park, "A W-Band Divide-by-Three Injection-Locked Frequency Divider With Injection Current Boosting Utilizing Inductive Feedback in 65-nm CMOS," in *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 5, pp. 516-519, May 2020, doi: 10.1109/LMWC.2020.2983014.
10. Q. Zou, K. Ma and K. S. Yeo, "A *V*-Band Wide Locking Range Divide-by-4 Injection-Locked Frequency Divider," in *IEEE Microwave and Wireless Components Letters*, vol. 28, no. 11, pp. 1020-1022, Nov. 2018, doi: 10.1109/LMWC.2018.2867366.
11. A. Hajimiri and T. H. Lee, "A general theory of phase noise in electrical oscillators," in *IEEE Journal of Solid-State Circuits*, vol. 33, no. 2, pp. 179-194, Feb. 1998, doi: 10.1109/4.658619.

# Discussion/Ideas

- Can some transmission line based approach be used to further isolate 2nd harmonic?
  - TL in between mixing devices? Short for fo, open for 2fo?
- Can some sort of feedback or amplifier approach be used to boost second harmonic?
- Better approach to switch/mixer in these topologies?