ARMMS RF and Microwave Society Meeting
April 4th and 5th
Milton Hill House
Steventon. Oxfordshire
United Kingdom.

# **Some Interesting Applications of Harmonic Mixers.**

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Abstract:
Harmonic or more correctly Sub-Harmonic or Sub-Harmonically Pumped Mixers have been with us since Major Armstrong of the US Army Signal Corps invented the Superhetrodyne Principle in 1917 (or was it actually invented by Reginald Fessenden in 1902???).
Harmonic mixing was used in early household radio receivers to save money since "The Wireless" was a luxury every family craved and harmonic mixing saved a valve!

In the modern Microwave and Millimetre Wave world sub-harmonically pumped mixers are often used because of the difficulty involved in the generation of SHF Local Oscillator signals.
This paper describes some "other" applications of Harmonic Mixers in Frequency Synthesizers where the devices are used to reduce costs and improve phase noise performance.

Discussion:
As part of some recent design work the author made use of a Sub-Harmonic Mixer which spawned an idea for the title of this paper.
"Some Interesting Applications of Harmonic Mixers" is a strange title since many engineers may consider the Harmonic Mixer is a somewhat boring component; I will attempt to change that!

1) The Superhetrodyne.
There is some evidence to suggest that, contrary to popular belief, the Superhetrodyne principal was discovered by the Canadian Reginald Fessenden in 1902.
Like many workers of the time he may have discovered the effect experimentally when working with Spark Gap Transmitters and receivers using "non-linear resistance detectors" (apparently known as "Goo Detectors" at the time!).
These devices consisted of a glass tube having electrodes at either end; the tube was filled with a mixture of Litharge (lead monoxide), Tin filings, Glycerin and Alcohol.

Figure 1 shows two resonators (the antennae) fed by a single spark gap.
If the two resonators were tuned to slightly different frequencies than a beat note could have been produced in the receiver (possibly similar to that in Figure 2) because the "Goo" detector also acted as a mixer.

Radio transmission technology took giant leaps with the invention of the vacuum diode by John Ambrose Fleming in 1904 and the triode by Lee De Forrest in 1907.

Radio Broadcasting was in full swing by the Twenties (The BBC started transmitting from Marconi House in November 1922 using the "2 LO" transmitter generating 100 Watts).
The race to manufacture and supply domestic radio receivers was officially on!
The big problem then was how to reduce costs? The simplest radios available at the time were "Crystal Sets" which, according to my father, had very poor performance.

The Rolls-Royce of radios were "Superhets"…but that meant at least four valves until Mr. Harry W. Houck invented his receiver using a Harmonic Mixer.

I discovered this work in an excellent paper presented at the 2009 IEEE MTT Symposium in Boston USA (Reference 1).

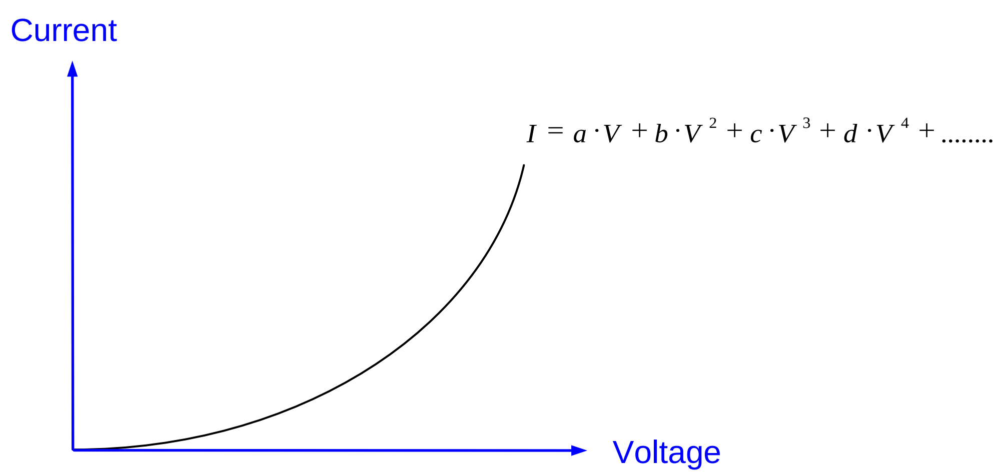
The "Radiola" broadcast receiver of 1924 is indeed an interesting application of a Harmonic Mixer. See Figure 3.
The triode tube acts as a local oscillator running at:

$$F_{LO} = (F_{SIG} - F_{IF})/2$$

The transformer B is tuned to the LO frequency and presents a low impedance to the signal frequency selected by the input tank circuit A.
If the he triode tube is operated at fairly low anode current its transconductance curve will be non-linear and mixing will occur producing current at IF in the transformer C.D. The tube also has some gain at IF even though it is oscillating at the sub-harmonic LO frequency.

2) Mixer Theory……A little Math:

Consider a non-linear resistor




The current through the device can be represented by a series.
If two alternating voltages having different frequencies are added in the device the resulting current will be of the form:

$$i = a\left(A\sin(\omega_1 t) + B\sin(\omega_2 t)\right) + b\left(A\sin(\omega_1 t) + B\sin(\omega_2 t)\right)^2 + c\left(A\sin(\omega_1 t) + B\sin(\omega_2 t)\right)^3 + .......$$

Expanding the second term:

$$i_2 = b\left(A\sin(\omega_1 t) + B\sin(\omega_2 t)\right)^2 = b\left(A^2\sin^2(\omega_1 t) + B^2\sin^2(\omega_2 t) + 2AB\sin(\omega_1 t)\sin(\omega_2 t)\right)$$

and:

$$2AB\sin(\omega_1 t)\sin(\omega_2 t) = AB\left(\cos\left((\omega_1 - \omega_2)t\right) - \cos\left((\omega_1 + \omega_2)t\right)\right)$$

These are the Sum and Difference frequencies

<u>Now if LO is at half frequency:</u>

$$i = a\left[A\sin\left(\frac{\omega_1}{2}t\right) + B\sin(\omega_2 t)\right] + b\left[A\sin\left(\frac{\omega_1}{2}t\right) + B\sin(\omega_2 t)\right]^2 + c\left[A\sin\left(\frac{\omega_1}{2}t\right) + B\sin(\omega_2 t)\right]^3 + .......$$

Expanding the second term:

$$i_2 = b\left[A\sin\left(\frac{\omega_1}{2}t\right) + B\sin(\omega_2 t)\right]^2 = b\left[A^2\sin^2\left(\frac{\omega_1}{2}t\right) + B^2\sin^2(\omega_2 t) + 2AB\sin(\omega_1 t)\sin(\omega_2 t)\right]$$

Further expanding the second term gives:

$$b\left[A^2\sin^2\left(\frac{\omega_1}{2}t\right) + B^2\sin^2(\omega_2 t) + 2AB\sin(\omega_1 t)\sin(\omega_2 t)\right] = b\left[\frac{A^2}{2}\left(1 - \cos(\omega_1 t)\right) + B^2\sin^2(\omega_2 t) + .....\right]$$

A component of the current (*i*) is therefore:

$$a\left[A\sin\left(\frac{\omega_1}{2}t\right) + B\sin(\omega_2 t)\right] + b\left[\frac{A^2}{2}\left(1 - \cos(\omega_1 t)\right) + .......\right]$$

(RF –LO term)

Expansion of the higher order terms in the series reveals harmonic mixing effects with rapidly diminishing amplitude as the harmonic number increases.

## 3) Some Harmonic Mixers:

The first time I encountered a Harmonic mixer was when I used a Hewlett-Packard Spectrum Analyser to look at the spectrum produced by a 30 GHz Gunn Effect Oscillator at AEI Semiconductors in Lincoln in 1972. See Figures 4a and 4b.

AEI Semiconductors became Marconi Electronic Devices in 1980 and it was here that I first used a harmonic mixer in a microwave signal source in 1987. See Figure 5.
The $8^{th}$ order Sub-Harmonic Mixer was used to down-convert the output of a voltage tuned Gunn Effect oscillator running at 94GHz to an IF at 2 GHz where the tuning characteristic of the Gunn VCO was linearised by a "Frequency Feedback Lineariser" circuit.

The device was improved over the next few years and was eventually miniaturized with all the microwave components integrated onto a single quartz Microstrip circuit.
See Figures 6a, 6b and 6c.
The original $8^{th}$ order sub-harmonic mixer was replaced by a $4^{th}$ order design having much lower conversion loss.

## 4) Harmonic Mixers in Frequency Synthesisers.

A sub-harmonic mixer can be considered to be an integrated mixer / multiplier combination whose multiplier only adds phase noise to the LO signal by a factor of 20 x log M where M is the Harmonic Number.
The "integrated multiplier" produces low level outputs which result in low amplitude IF signals but these signals may be used provided that they are above the noise floor of the PLL system.
Figure 7 shows harmonic mixer used to replace a multiplier in a frequency converting PLL Synthesiser.

This principle was used in the CELERITEK (now part of Teledyne Microwave) "Tiger Synthesiser in 1999. See figure 8.
This device was intended to be used as a dual local oscillator in a transceiver for the Ill-fated LMDS (Local Multipoint Distribution Services) system.
The two identical PLLs use down-conversion within the loops which was accomplished with third order Harmonic Mixers.

## 5) Commutative mixers in Sub-Harmonic Mode

The microwave and millimetre wave frequency Harmonic Mixers described above have all made use of single diodes or anti-parallel pairs of diodes on some form of Microstrip circuit.
I recently experimented with a harmonic mixer design to operate over a 10% bandwidth in C-Band see Figure 9.

I wanted to use the mixer with a harmonic number of five; my problem was that the Microstrip elements were quite large especially the radial stub whose radius was approximately 6mm.
The device had high conversion loss in C-Band; using a 1 GHz Local oscillator I measured conversion loss greater than 30 dB.
I had once read a Technical Note published by Watkins-Johnson and written by Bert. C. Henderson (Reference 2) where he described the use of ring mixers in sub-harmonic mode; I therefore decided to perform an experiment using a Minicircuits ZX05 – 63LH-S+ packaged ring mixer.
I used a Local Oscillator signal at 1GHz at a level of +13dBm and measured the IF output for 0 dBm input signals at 1.1 GHz, 2.1 GHz, 3.1 GHz, 4.1 GHz and 5.1 GHz (IF at 100 MHz).

The results are summarized below.

| LO Frequency (+13dBm) | Signal Frequency (0dBm) | IF Amplitude (100 MHz |
|---|---|---|
| 1000 MHz | 1.1 GHz | -7.2 dBm |
| 1000 MHz | 2.1 GHz | -23.0 dBm |
| 1000 MHz | 3.1 GHz | -16.4 dBm |
| 1000 MHz | 4.1 GHz | -37.9 dBm |
| 1000 MHz | 5.1 GHz | -23.0 dBm |

These are interesting results!
The device obviously works very well in the odd harmonic modes with M = 1, 3 and 5; Performance in the even order modes is less encouraging.
This Ring Mixer is available as a surface mount component from Minicircuits (Part number SIM63-LH+). See Figure 10.
It is interesting to note that this mixer is approximately the same size as my radial choke!

<u>Summary</u>

In this paper I have presented some information on Mixers and Harmonic Mixers….a little history, some mathematics, some applications in Frequency Synthesisers and some measurement results.
I hope you found it interesting!

References:

1) History of Sub-Harmonic Pumped Mixers
Edmar Camargo
Workshop WME 2009 IEEE International Microwave Symposium
Boston. Massachusetts USA

2) “A highly linearised mm-wave voltage controlled oscillator for FMCW radar applications”
A. David Williams
Solid State Components for Radar,
IEE Colloquium on Radar Systems
Page(s): 6/1 – 6/15
12 Feb 1988

3) Watkins-Johnson “Tech-Note”
Mixers Part 2. Theory and Technology
Bert. C. Henderson

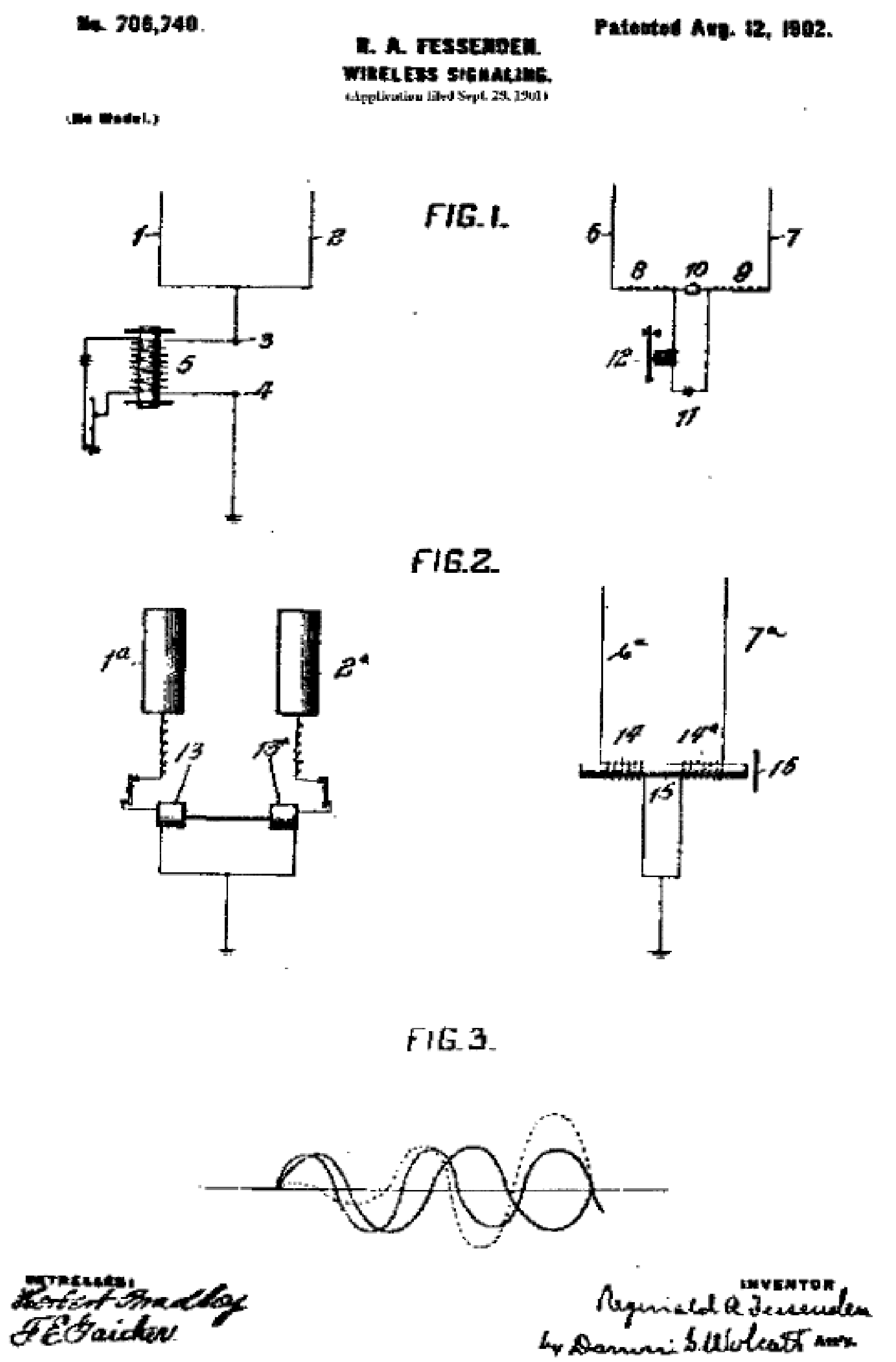



Figure 1. Fessenden' Heterodyne Patent 1902.

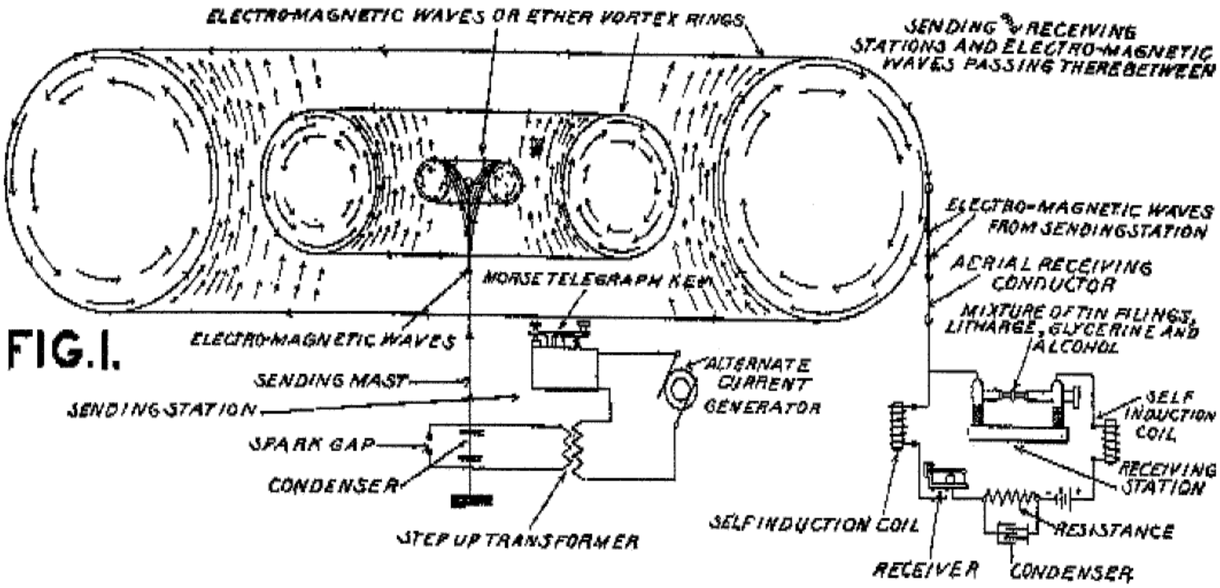



Figure 2. De Forests Radio Transmission System.
*Exhibit of the Department of Interior Patent Office: Government Building, Louisiana Purchase Exposition*, 1904

# Early Radio Days …

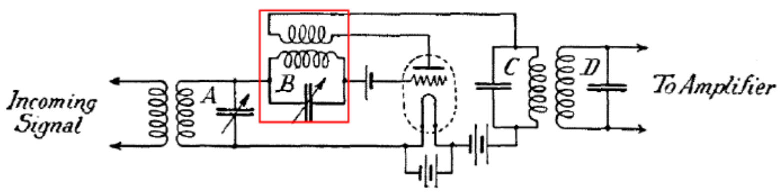
IMS 2009
JUNE 7-12
BOSTON MA

- **Vacuum tube triode receiver**

  **RCA_1924 – “Radiola Super-Heterodyne Second Harmonic Receiver” by Harry W. Houck**

  **Self Oscillating Mixer**

  - **Circuit A tuned to incoming signal (RF- Amp)**
  - **Circuit B tuned at fLO = one-half the incoming signal +/- IF**
  - **Circuits C & D tuned to IF (IF – Amp)**




The Super-Heterodyne – Its Origin, Development, And Some Recent Improvements. Proceedings of The Institute of Radio Engineers, New York, March 5, 1924.

Figure 3. The “Radiola” Broadcast Receiver

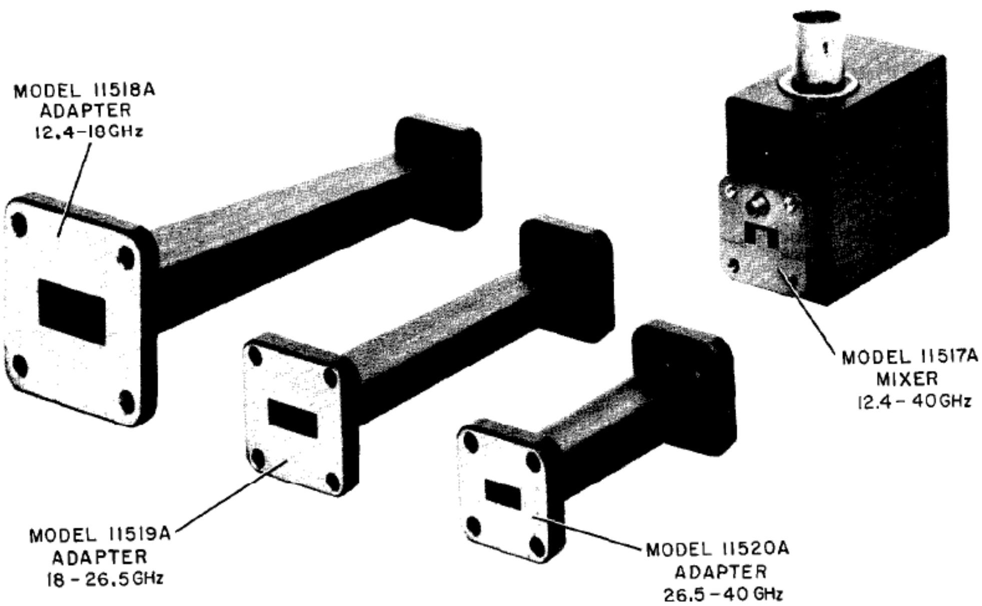



Figure 4a. Hewlett-Packard Harmonic Mixer. 1974

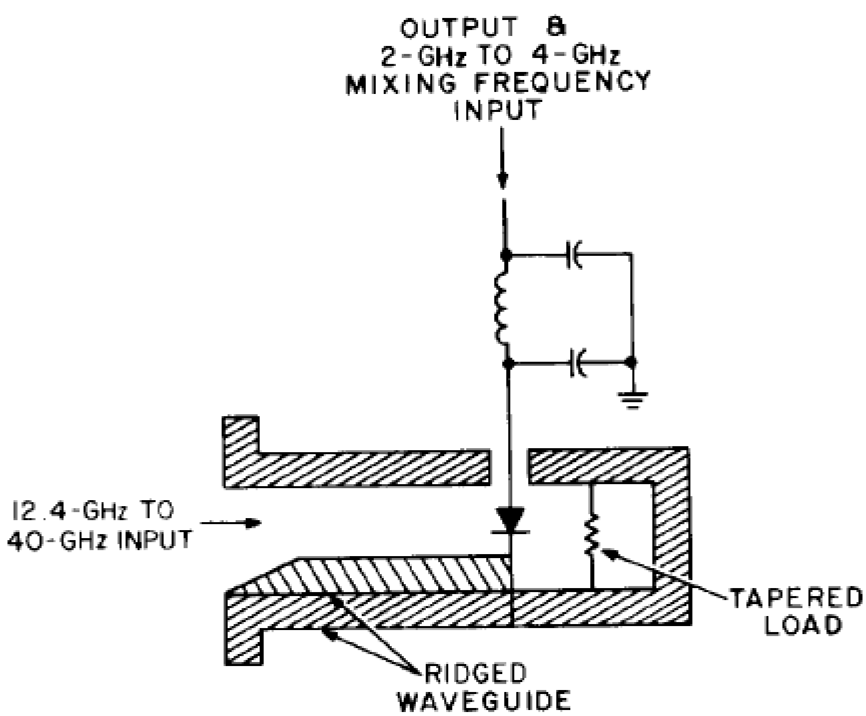



Figure 4b. Hewlett-Packard Harmonic Mixer construction

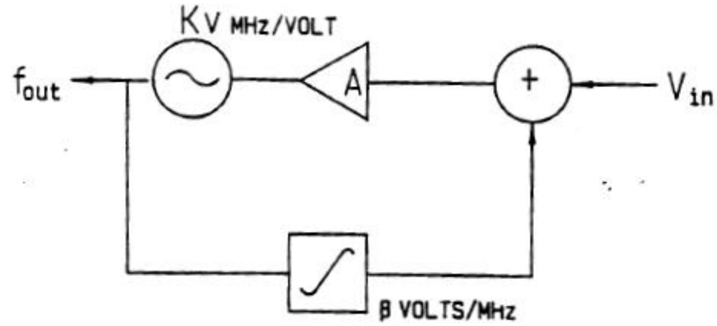



FIG.6 DISCRIMINATOR STABILIZIED
TUNABLE OSCILLATOR

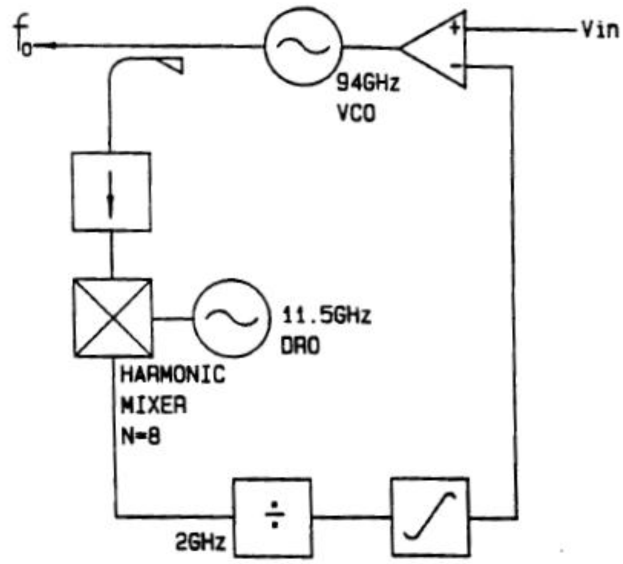



FIG.7 94GHz VCO
WITH CLOSED LOOP LINEARISATION

Figure 5. Reprinted from "A highly linearised mm-wave voltage controlled oscillator for FMCW radar applications"
Williams, D.
This paper appears in: Solid State Components for Radar,
IEE Colloquium Radar Systems
Page(s): 6/1 – 6/15
12 Feb 1988

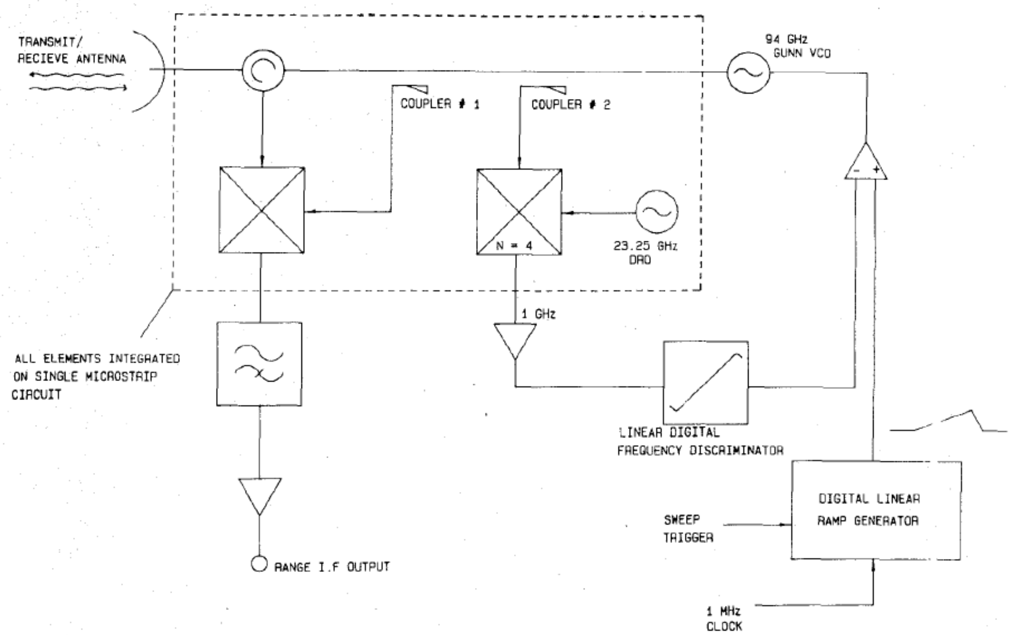



Figure 6a. FMCW Radar Schematic 1991

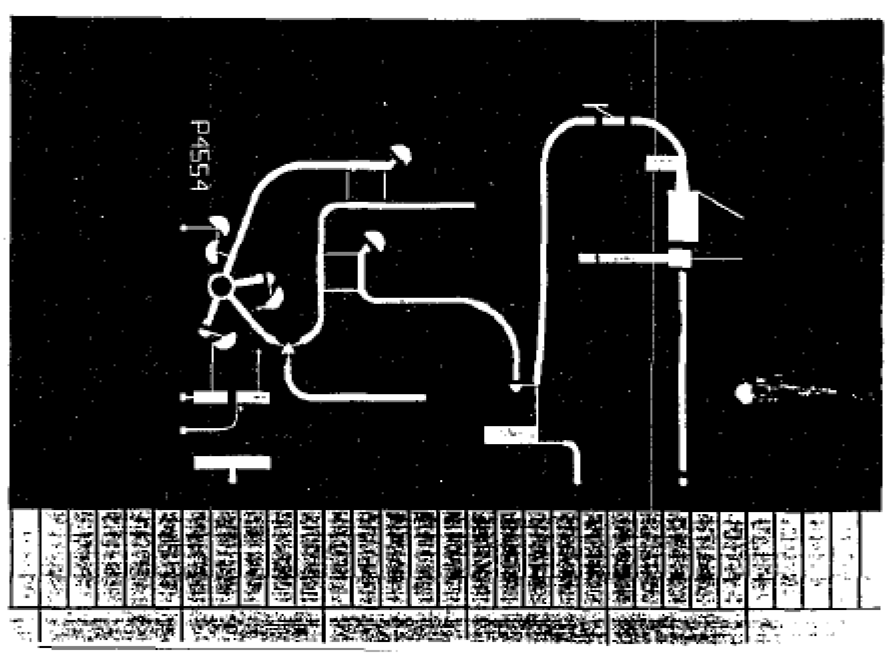



Figure 6b. FMCW RADAR Quartz Microstrip Circuit 20 x 13.5 x 0.127mm

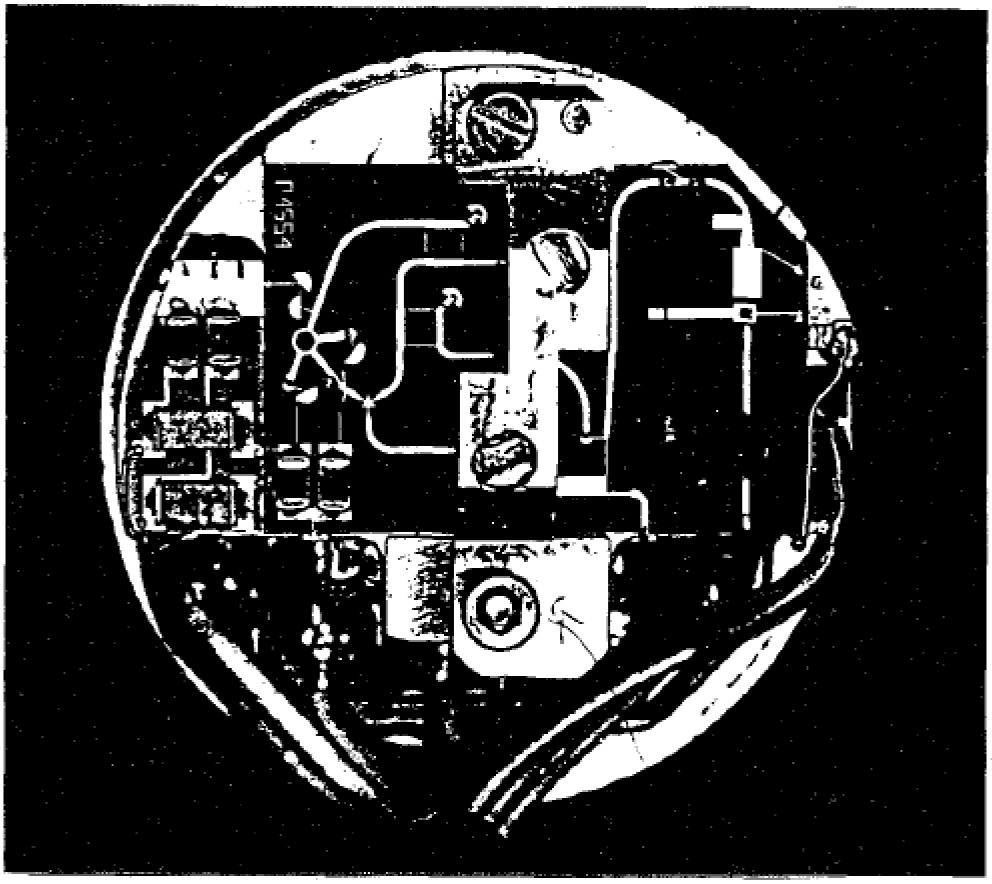


Figure 6c Assembled FMCW RADAR Head 25mm diameter.

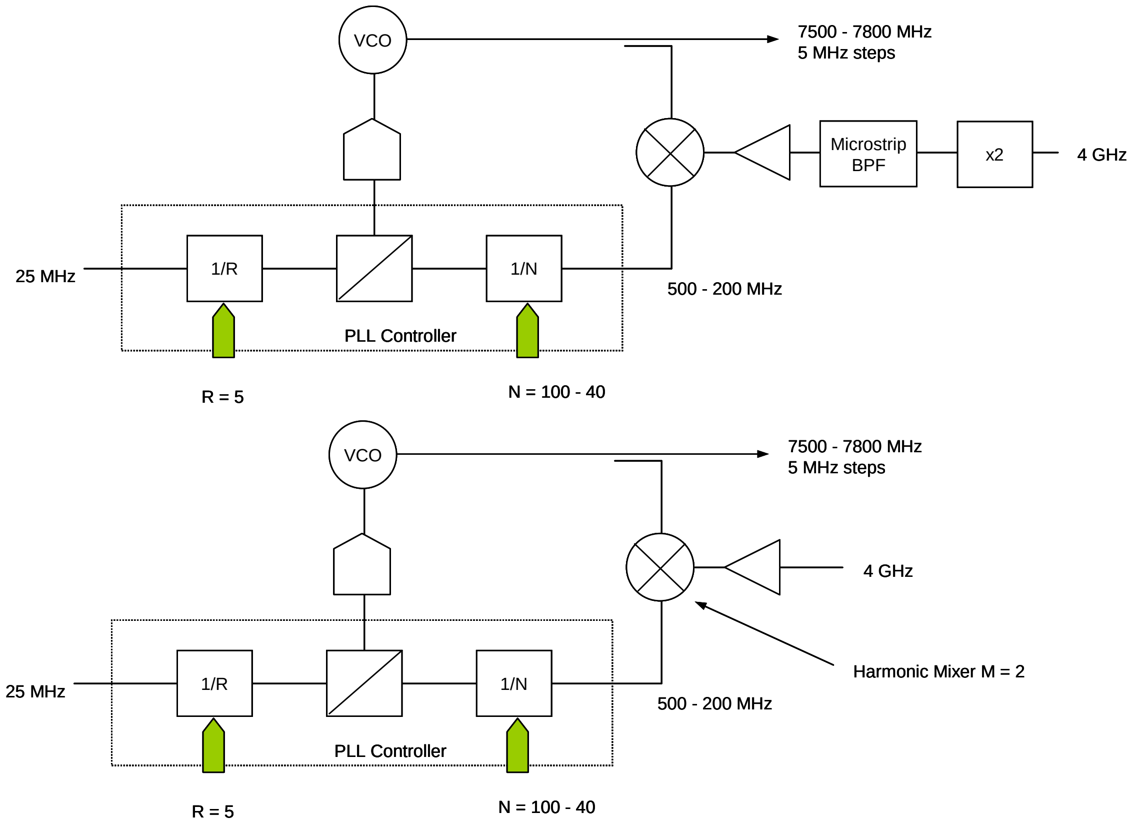



Figure 7. Application of a Harmonic Mixer within a PLL

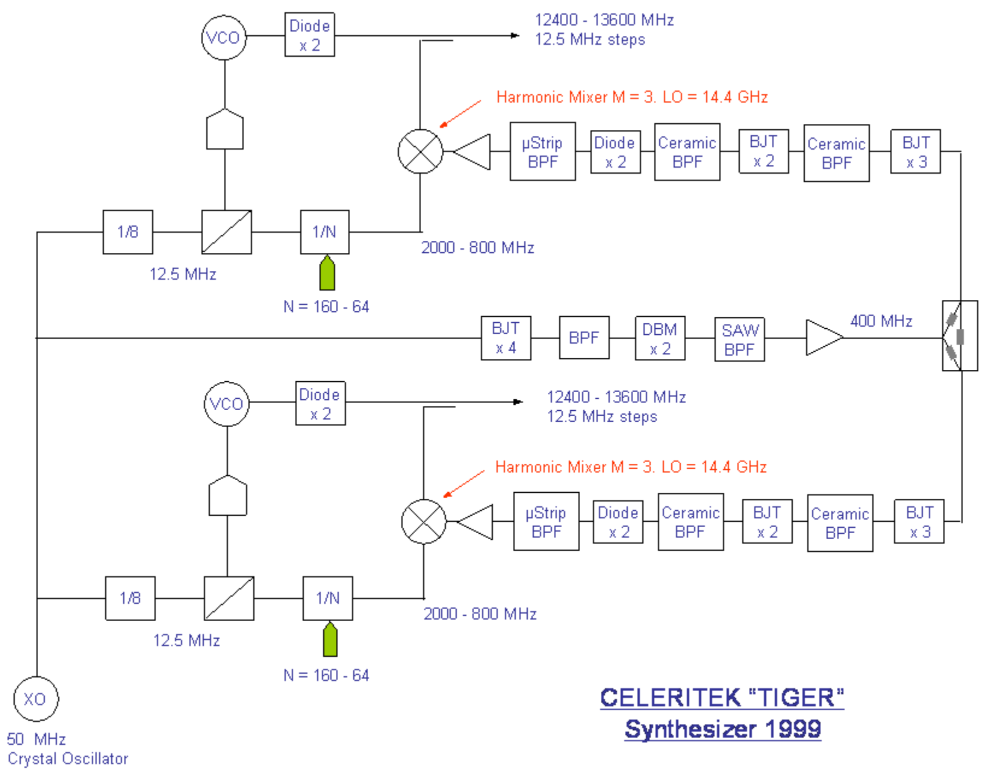



Figure 8. Celeritek “Tiger” Synthesizer

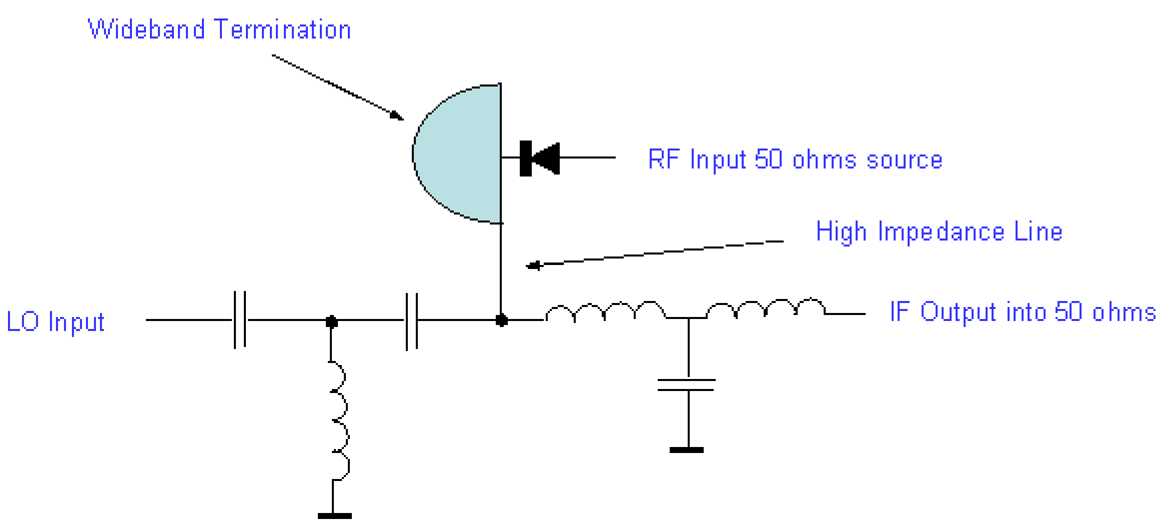



Figure 9. Wideband Harmonic Mixer Experiment

*Ceramic Surface Mount*

# Frequency Mixer WIDE BAND

## SIM-63LH+

Level 10 (LO Power +10 dBm) 750 to 6000 MHz

CASE STYLE: HV1195
PRICE: $8.95 ea. QTY (10-49)

*+ RoHS compliant in accordance with EU Directive (2002/95/EC)*

*The +Suffix has been added in order to identify RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications.*

### Maximum Ratings

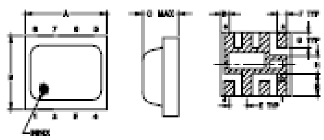
| | |
|---|---|
| Operating Temperature | -40°C to 85°C |
| Storage Temperature | -55°C to 100°C |
| RF Power | 50mW |

For extended temperature range, consult factory.
Permanent damage may occur if any of these limits are exceeded.

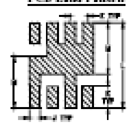
### Pin Connections

| | |
|---|---|
| LO | 8 |
| RF | 4 |
| IF | 2 |
| GROUND | 1,3,5,6,7 |

### Outline Drawing



PCB Land Pattern



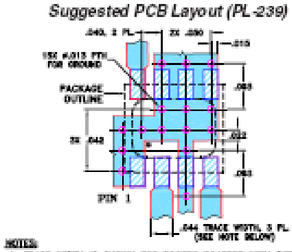
Suggested Layout, Tolerance to be within ±.002

### Outline Dimensions (inch/mm)

| A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| .200 | .180 | .087 | .025 | .050 | .028 | .043 |
| 5.08 | 4.57 | 2.21 | 0.64 | 1.27 | 0.71 | 1.09 |

| H | J | K | L | M | N | wt |
|---|---|---|---|---|---|---|
| .050 | .030 | .060 | 0.238 | 0.144 | 0.065 | grams |
| 1.27 | 0.76 | 1.52 | 6.05 | 3.66 | 1.65 | 0.08 |

*Demo Board MCL P/N: TB-382*
*Suggested PCB Layout (PL-239)*




NOTES:
1. TRACE WIDTH IS SHOWN FOR ROGERS RO4350B WITH DIELECTRIC THICKNESS .020" ± .0015"; COPPER: 1/2 OZ. EACH SIDE. FOR OTHER MATERIALS TRACE WIDTH MAY NEED TO BE MODIFIED.
2. BOTTOM SIDE OF THE PCB IS CONTINUOUS GROUND PLANE.

DENOTES PCB COPPER LAYOUT WITH SMOBC (SOLDER MASK OVER BARE COPPER)

DENOTES COPPER LAND PATTERN FREE OF SOLDER MASK

### Features

- wide bandwidth, 750 to 6000 MHz
- low conversion loss, 6.2 dB typ.
- excellent L-R isolation, 34 dB typ.
- LTCC double balanced mixer
- tiny size, low profile, 0.09"
- useable as up and down converter
- aqueous washable
- protected by US patent 7,027,795

### Applications

- cellular
- defense & weather radar
- defense communications
- PCN
- WCDMA
- WIFI
- blue tooth
- VSAT
- ISM

### Electrical Specifications

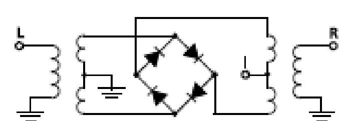
| FREQUENCY (MHz) LO/RF $f_L$-$f_U$ | IF | CONVERSION LOSS* (dB) Typ. | σ | Max. | LO-RF ISOLATION (dB) Typ. | Min. | LO-IF ISOLATION (dB) Typ. | Min. | IP3 at center band (dBm) Typ. |
|---|---|---|---|---|---|---|---|---|---|
| 750-6000 | DC-1500 | | | | | | | | |
| 750-1700 | | 6.3 | 0.1 | 7.3 | 37 | 31 | 30 | 20 | 12 |
| 1700-2000 | | 6.6 | 0.1 | 7.5 | 37 | 32 | 20 | 12 | 18 |
| 2000-3100 | | 5.8 | 0.1 | 7.2 | 32 | 25 | 22 | 12 | 12 |
| 3100-3800 | | 5.7 | 0.1 | 7.0 | 30 | 25 | 25 | 15 | 15 |
| 3800-6000 | | 8.0 | 0.2 | 9.3 | 30 | 22 | 20 | 13 | 15 |

1 dB Compression: +3 dBm typ.
* Conversion loss at 30 MHz IF. σ is a measure of repeatability from unit to unit.

### Typical Performance Data

| Frequency (MHz) RF | LO | Conversion Loss (dB) LO +10dBm | Isolation L-R (dB) LO +10dBm | Isolation L-I (dB) LO +10dBm | VSWR RF Port (:1) LO +10dBm | VSWR LO Port (:1) LO +10dBm |
|---|---|---|---|---|---|---|
| 740.00 | 771.00 | 6.12 | 39.29 | 26.22 | 1.99 | 7.05 |
| 850.00 | 881.00 | 5.79 | 36.91 | 27.35 | 1.51 | 4.55 |
| 1000.00 | 1031.00 | 6.24 | 40.47 | 28.20 | 2.63 | 2.78 |
| 1200.00 | 1231.00 | 6.27 | 42.51 | 30.04 | 3.21 | 1.54 |
| 1500.00 | 1531.00 | 6.05 | 36.17 | 42.37 | 2.94 | 2.15 |
| 1800.00 | 1831.00 | 6.53 | 37.46 | 21.72 | 3.22 | 2.96 |
| 2100.00 | 2131.00 | 6.29 | 36.76 | 17.14 | 3.00 | 2.64 |
| 2400.00 | 2431.00 | 5.47 | 35.23 | 21.65 | 2.01 | 2.45 |
| 2700.00 | 2731.00 | 5.11 | 31.43 | 23.85 | 1.75 | 1.87 |
| 3000.00 | 3031.00 | 5.05 | 30.30 | 26.15 | 1.34 | 1.30 |
| 3400.00 | 3431.00 | 5.53 | 30.24 | 23.55 | 1.44 | 1.45 |
| 3800.00 | 3831.00 | 6.01 | 28.84 | 20.37 | 2.40 | 2.23 |
| 4200.00 | 4231.00 | 7.01 | 30.59 | 18.41 | 3.57 | 3.00 |
| 4500.00 | 4531.00 | 8.08 | 32.32 | 17.66 | 4.84 | 3.45 |
| 4800.00 | 4831.00 | 8.28 | 31.53 | 21.57 | 5.04 | 3.96 |
| 5100.00 | 5131.00 | 7.96 | 28.60 | 26.68 | 3.55 | 3.05 |
| 5400.00 | 5431.00 | 7.36 | 28.72 | 23.26 | 3.65 | 3.13 |
| 5700.00 | 5731.00 | 7.43 | 28.75 | 20.86 | 2.99 | 3.26 |
| 5850.00 | 5881.00 | 7.75 | 27.90 | 20.28 | 2.82 | 2.87 |
| 6000.00 | 6031.00 | 7.66 | 27.87 | 21.39 | 2.48 | 2.13 |

### Electrical Schematic

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IF/RF MICROWAVE COMPONENTS



REV. OR
M105046
SIM-63LH+
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071129
Page 1 of 2

Figure 10. Minicircuits SIM-63LH+ surface mount mixer.