Dusting off the Lecher Lines

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Introduction

It is quite some time since the article by Howes [1], concerning Lecher Lines, graced the pages of “Physics Education”. Historically, however, this apparatus invented in 1890 [2] was a pivotal point in the study of Radio Frequency (r.f.) waves as it allowed the wavelength/ frequency of such waves to be measured and, perhaps on this account, the topic should be given a more prominent place in the curriculum.
In the 1960’s and 1970’s experiments with Lecher Lines were popular since they provided a means of unifying the physics of waves; standing waves detected on Lecher Lines had much in common with standing waves on vibrating strings or vibrating columns of air in an organ pipe. The cherished experiments: Kundt’s tube or “Measurement of the frequency of “Mains” electricity with a sonometer” were commonly used at A-level and beyond. The experiment also provided a good introduction to the subject of transmission lines. But the advent of Network Analysers in the 1980’s removed the need to employ standing wave techniques to study the propagation of r.f. and microwave radiation and, indeed, the slogan with practitioners of the time was S.O.S, Stamp Out Standing-waves. Inevitably Lecher Lines were placed on the top of cupboards – out of sight and out of mind.
In an attempt to redress the balance the following experiment on Lecher Lines will be presented. The apparatus can be constructed for a modest cost and the constructional details should not be beyond the capabilities of a Physics Laboratory workshop. Of course, a spanking new apparatus can still be purchased from LD Didactic and the Physics Leaflet P 3.7.3.1, available on-line, gives a full description of several experiments that can be carried out with the apparatus.
For motivation of the faint hearted, why not watch one of the many presentations on U-tube?

Brief theoretical details of Transmission Lines

The most obvious transmission lines that pervade our environment are electricity power lines and telephone cables. These transmit either power or information from one location to another. Another example is the familiar coaxial cable which conveys the TV broadcast signals from an antenna into a receiving unit.
Now, how do we deal with these lines? They do not appear to conform to normal electronic components such as resistors, capacitors, inductors and the like.

But, if we cut the coaxial cable into small pieces, say, lengths of 10 cm, then we can see that these small elements do have capacitance and inductance (about 10 pF and 3 μH for a 10 cm length) and then one can reconstruct the cable by adding all the elements together again. (It is assumed here that the line has no resistive loss). Fig. 1 shows how the elements are arranged.

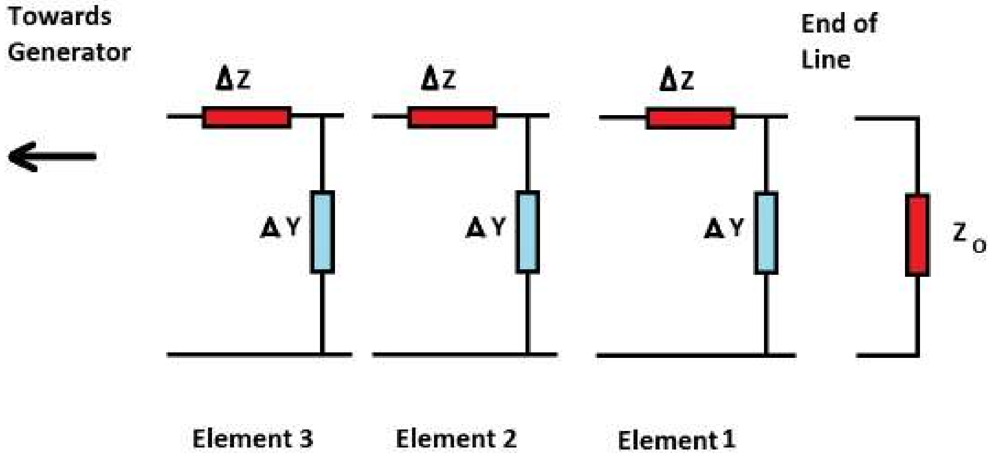


Figure 1 Circuit elements which constitute a transmission line

The red components have impedance values and the blue components depict admittance values. As indicated above, the component values for a coaxial line will be: $\Delta Z = j\,\omega L$, and $\Delta Y = j\,\omega C$ with the L and C values given above.

Assume that the end of the line has an impedance, Z_O, and element 1 is connected to it. The new input impedance, Z_{in}, can easily derived:

$$Z_{in} = \Delta Z + \frac{Z_O}{\Delta Y . Z_O + 1} \qquad (1)$$

A very simple analysis can be carried out if it is assumed that, Z_{in}, has a value of Z_O and equation 1 can then be simplified, by neglecting the very small term $\Delta Z . \Delta Y . Z_O$, to give

$$(Z_O)^2 = \Delta Z / \Delta Y = L/C \qquad (2)$$

The next element can now be added and, providing that equation 2 is again satisfied, the new input impedance is Z_O. The whole coaxial line is assembled from all the remaining elements and a generator can now be attached to the final element. As far as the generator is concerned it is simply being connected to an impedance of value Z_O. In reality, however the signal from the generator cascades down the line until it meets the real component, Z_O, where it is totally dissipated. This special value of impedance is called the characteristic impedance of the line and is determined from the physical dimensions of the line. Such a line is ideal since any signal from a generator will be conveyed to the end of the line and then be dissipated in the final component called the load or termination. The formula for Z_O for a parallel wire transmission line where the wire diameter is d and the wire separation is D is given by equation (3):

$$Z_0 = \frac{1}{\pi}\sqrt{\frac{\mu_0}{\varepsilon_r \varepsilon_0}}\ln\left(2D/d\right) \qquad (3)$$

If the relative permittivity, ε_r, of the medium in which the wires are placed is unity then the equation simplifies to $Z_0 = 276 \, Log_{10}(2D/d)$ as given by Howes [1] .

A full analysis of transmission lines is more complex then that given above but suitable treatments can readily be found on-line. The reader is directed to an e-Text written by Hay and Buck [3]. The full analysis shows that waves travel backwards and forwards on a line that is not terminated by the characteristic impedance and therefore standing waves are established. With regard to the present experiment, it is these standing waves that allow the wavelength and hence frequency of any signal source to be determined. These are illustrated in Fig 2 for a full wavelength.

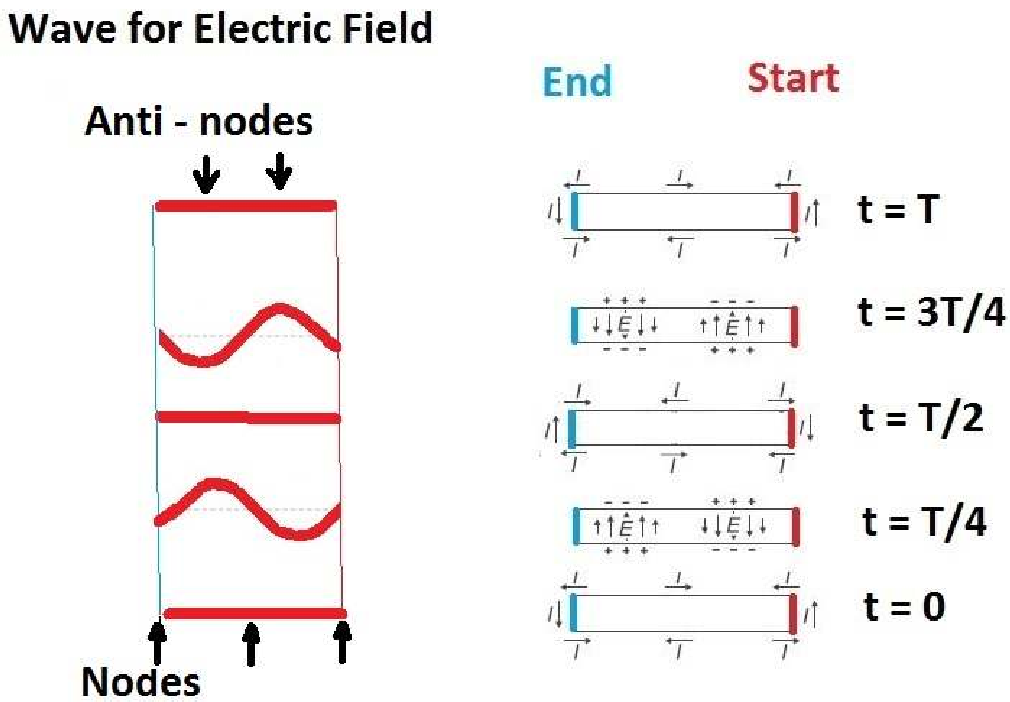


Figure 2 Standing Waves on Lecher Lines (T is the period)

Apparatus

The following Lecher Line apparatus was constructed quite simply by fixing two galvanized steel rods to a piece of waste plastic guttering. The length was 1.0 m with rod diameter 5 mm and rod separation of 10.5 cm. The lines plus a sliding detector are shown in Fig 3.

Figure 3 Lecher Line apparatus (rod diameter, d = 5.0 mm, separation 10.5 cm)

Electrical contact was made to the wires with an N-type connector and the wires were tapered inwards so that the passage of r.f. waves from the N-type terminal to the Lecher Lines would be less abrupt.
A simple radio wave detector, Fig 4, has already been described in this journal [4] and such a circuit has proved satisfactory for detecting the waves along the lines.

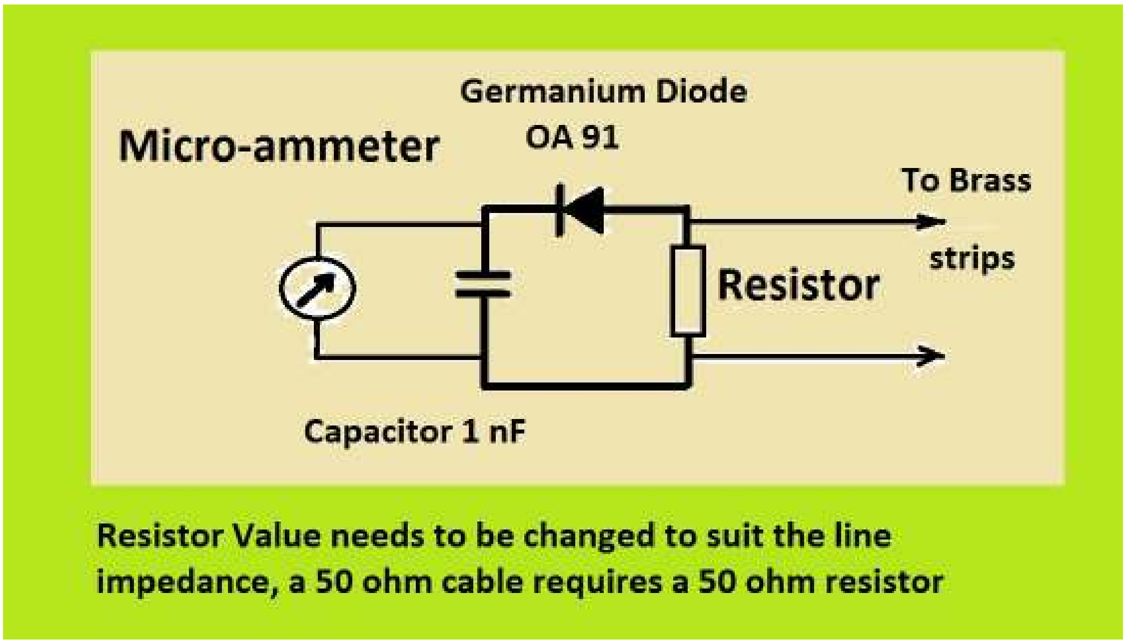


Figure 4 Simple diode detector as described in reference [4].

The circuit is mounted under the meter as shown in Fig. 5.

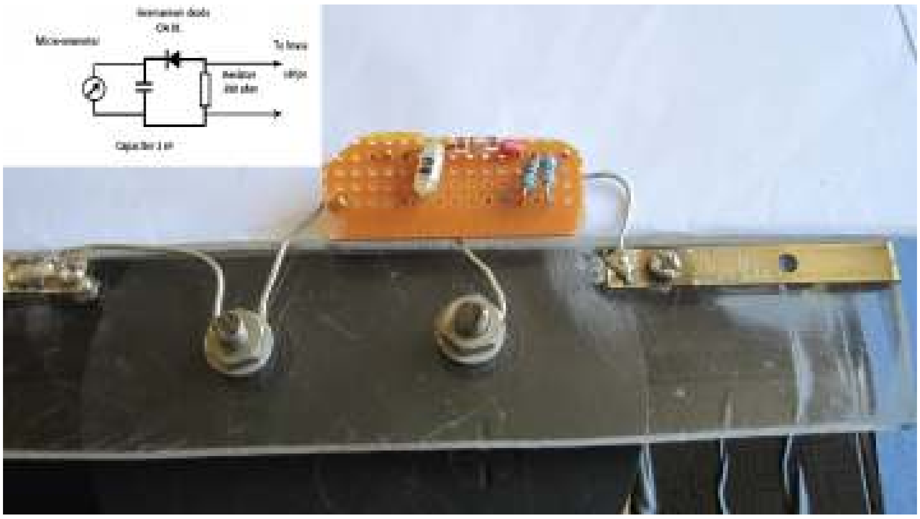


Figure 5 Detection circuit for r.f. signal on Lecher Lines (brass strips make contact with lines

The final part of the apparatus is the signal source. A confession must be made at this point since attempts to construct both circuits (Fig's 1 and 2 of Howes' work [1]) were a failure : the strip-line circuit gave an output at 60 MHz and the other circuit refused to oscillate. Signal sources are now available in kit form (Appendix 1) but for the present experiment, a ready-made varactor tuned oscillator, VTO, (model ZX 65 – 850) was purchased from Mini-Circuits. The VTO required a fixed voltage of 5 V and a variable voltage from 0 to 25 V for tuning. Little current is needed for tuning so a multi-turn potentiometer was connected to a fixed 25 V source and this allowed fine tuning of the signal source. It must, however be stressed that the power from the Mini-Circuits VTO is quite low (10 mW) compared to the oscillator given to Howes [1] which was claimed to give an output close to 1 W. The signal source is attached to the "near" end of the Lecher Lines as shown in Fig 6.

Figure 6 Voltage tuned oscillator, VTO, (Mini-Circuits) attached to the line

The apparatus is made more versatile if both the ends of the line are fitted with N-type connectors and an additional detector is attached to the “far” end of the line. The apparatus can now be used to detect resonances on the line and, for half a wavelength trapped on the line, the signal would have a frequency of 150 MHz (Further resonances : 300 MHz for 1 λ , 450 MHz for 3λ/2, 600 MHz for 2λ , 750 MHz for 5λ/2, etc . Also, note that the lines are of length somewhat less than 1m as the N-type connectors with suitable adaptors add a few cms to the geometrical length)

Results

(a) Transmission characteristics of Lecher Lines

The voltage on the VTO was scanned by using a motorized potentiometer. The detector output was recorded with an ADC – 100 (Pico Tech. Ltd) and graphically displayed as in Fig 7

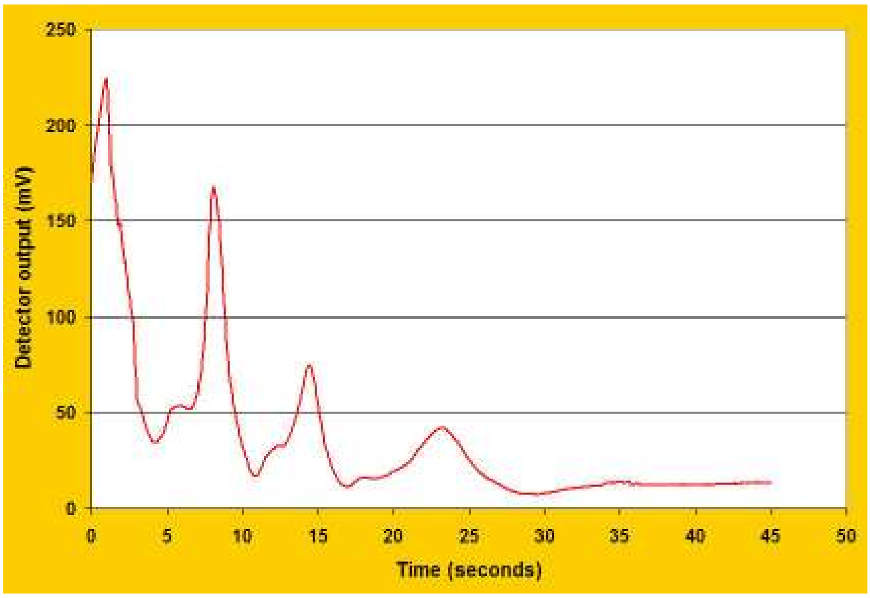


Fig 7 Detector output as signal frequency is increased

Relatively sharp peaks occur as the closed Lecher Lines exhibit resonance due to trapped waves as described in Fig. 2. Although time appears on the x-axis this signifies the time that the motor is running and turning the potentiometer to ramp up the varactor voltage so increasing the frequency of the VTO. Only an approximate voltage is obtained during scanning and a manual adjustment, later, gives greater accuracy of this varactor voltage at peak.

For the four well-defined peaks in Figure 7 the voltages were.. 0.05, 4.3, 9.3 and 15.6 and the fifth peak was not distinct enough for measurements to be made.

As mentioned before the resonances for 1m lines (in MHz) are 150, 300, 450, 600, 750, 900, etc and our first peak will correspond to 300 MHz as the ZX 95-850 oscillator has a lower limit at this frequency.

The calibration graph is presented in Fig 8

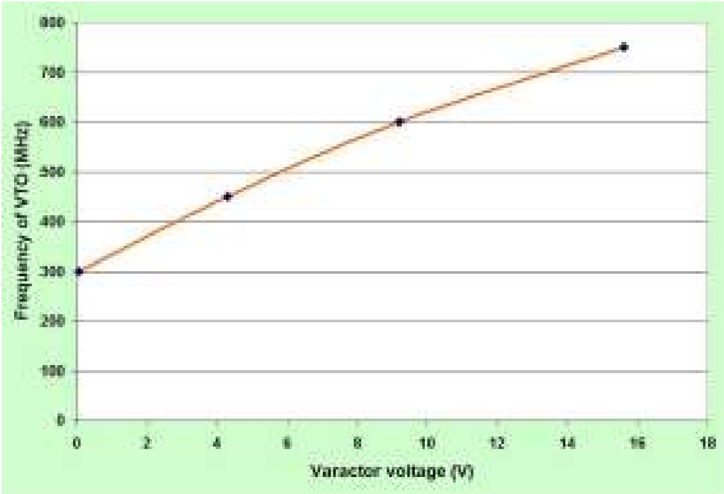


Fig 8 Calibration of a Varactor Tuned Oscillator using standing waves on Lecher Lines

Even though only four data points were available, the graph compares favorably with that given in the Mini-Circuits data sheet (Appendix 2). By far the best way of identifying the resonance modes along the lines is to use one's hand as in Fig 9.

Fig 9 Identifying nodes and anti-nodes of standing wave modes on Lecher Lines (hands-on approach)

Since the signal source has a very low power one can safely place one's hand across the lines and move it backwards and forwards. At the position of a node the transmission is hardly altered whereas with the hand placed at an anti-node one observes severe attenuation. It is simply that the electric field is absorbed by the tissues and fluids in the hand. It may be noted that a piece of Perspex placed across the lines gives little change when moved from node to anti-node. However, when a slab of Perspex approx. 5 mm in thickness covers the lines then all resonances occurs at lower frequencies thus indicating that the wavelengths have been compressed (for lines totally immersed in a material the relationship for wavelength change is $\lambda_{material} = \lambda_{free\ space}$/root permittivity [3]).

(b) Matching Lecher Lines

The characteristic impedance of the Lecher Line is given by Equation (3) and for the dimensions of the lines in the present study we find Z_O to be approximately 450 ohms. With the lines either open or shorted the sliding detector (Fig 2) give scale readings of 80 max and 10 min.

Terminating the lines with a resistor of value, 470 ohms did reduce standing waves to a smaller level, 50 max and 40 min but the resistor was only clipped to the line and a residual mismatch was very likely to be present.

(c) Examination of magnetic fields.

A loop of wire was attached to the sliding detector (Fig 3) as a replacement to the brass strips. This is given in Figure 10.

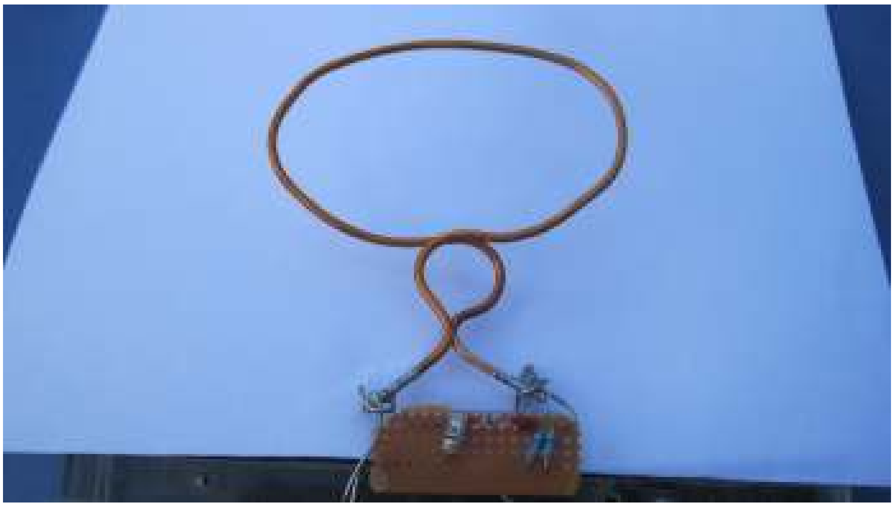


Figure 10 Coil attached to the rectifying circuit mounted on the 100 micro-ammeter.

As expected the maximum values occurred at the nodes for the electric field but the signal was smaller by a factor of about five. Further investigations need to be made with different loop geometries

Conclusion

A low power Lecher Lines apparatus has been constructed which complies fully with present Health and Safety standards regarding electromagnetic emissions. The concept of matching transmission lines has been qualitatively demonstrated and the apparatus needs to be refined somewhat to provide a better way of attaching the matching resistor.

The signal source has been calibrated with an analysis of standing waves and the student can gain a full understanding of resonant structures with this open arrangement. Although Howes [1] mentions the whole apparatus being submersed in a tank of water to investigate the effect of water on r.f. transmission, one could place troughs of liquid on the line to see if electric field absorption occurs at the anti-nodes.
Partially covering the lines with a dielectric does result in wavelength compression and a qualitative assessment of permittivity of materials would be possible by placing them on or between the Lecher Lines and noting the wavelength reduction.
The experiment showed that magnetic field maxima coincided with nodes in electric field but the signal level was rather weak. Further developments are necessary with the loop detector to increase the signal.

References

[1] R. W. Howes (1980) “UHF power transistors and Lecher line oscillators”, Phys. Ed., Vol, 15 (1), p 49.

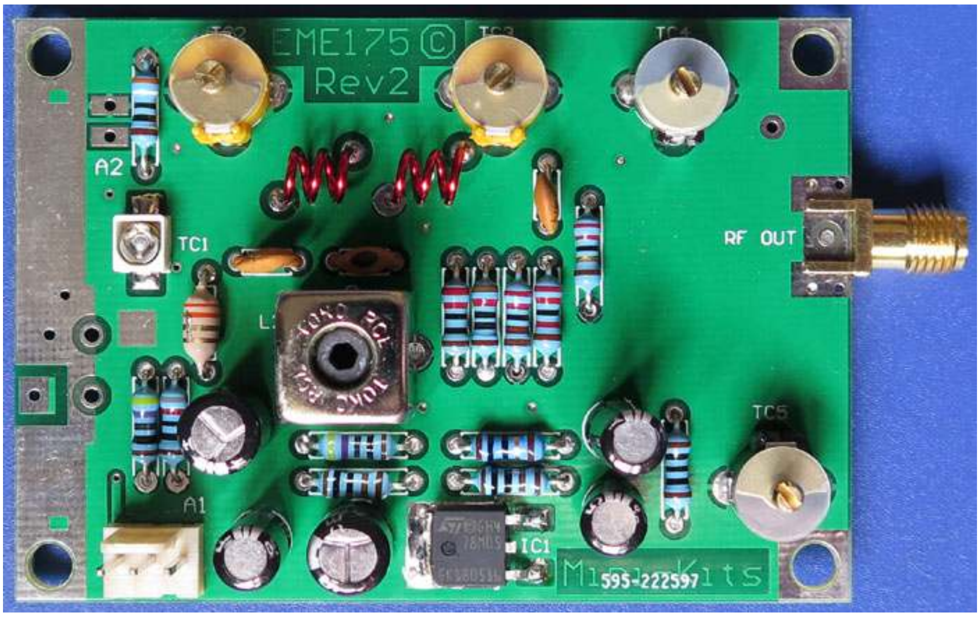
[2] E.Lecher (1890) “Eine studie uber electrische Resonanzerscheinungen”, Wiedemann Annalen, 41, p 850.

[3] W. H. Hayt and T. A. Buck “Engineering Electromagnetics”, 6th Edition (2001) Chapter 13. Available on-line as Interactive e-Text.

[4] J. Hare (2010) “A simple demonstration for exploring the radio waves generated by a mobile phone”, Phys. Ed., Vol 45 (5), p 481

Appendix 1

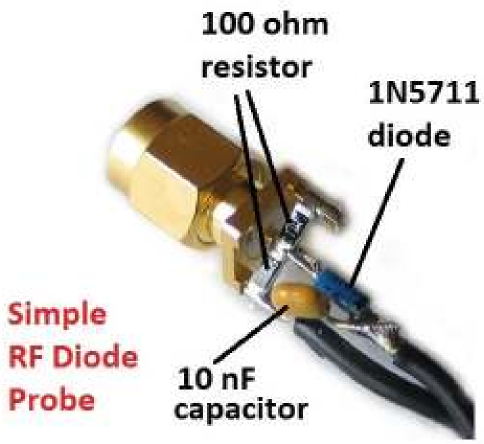
Kit of parts available from Minikits for an r.f. oscillator, product code EME 175 KIT 1 (photograph kindly provided by Minikits)



Tuning is possible and circuits are suggested for a detector as follows:-

Simple RF Diode Probe:

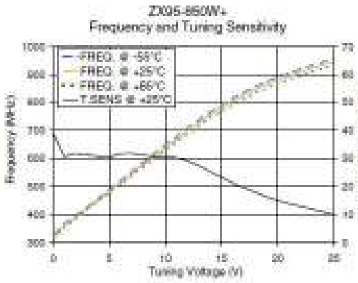
If you don't have any test equipment to tune the oscillator for maximum RF output, then a simple RF Diode probe can be constructed. This circuit is so simple that there is no need for a circuit diagram. The probe uses a SMA Male PCB mount socket with two 100ohm resistors in parallel, a 1N5711 Schottky diode, and 10nF filter capacitor. The probe output uses a short length of figure 8 type cable to connect to a digital multimeter. The voltages to the left were measured at 576MHz and may be slightly different with component tolerance and construction. Typical output @ 576MHz from the EME175 Kit was 0.956v DC or +10dBm.

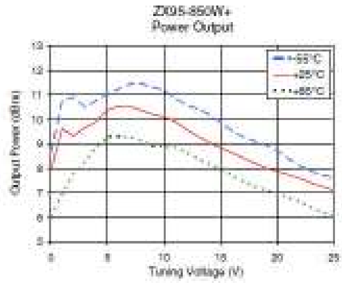


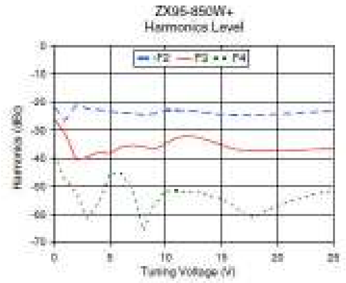
DC Output Voltage	dBm @ 576MHz	Power
1.38v	+13dBm	
0.956v	+10dBm	10 mW
0.843v	+9dBm	
0.742v	+8dBm	
0.652v	+7dBm	
0.572v	+6dBm	
0.497v	+5dBm	
0.435v	+4dBm	
0.380v	+3dBm	
0.330v	+2dBm	
0.288v	+1dBm	
0.248v	+0dBm	1 mW
0.115v	-5dBm	
0.048v	-10dBm	0.1 mW

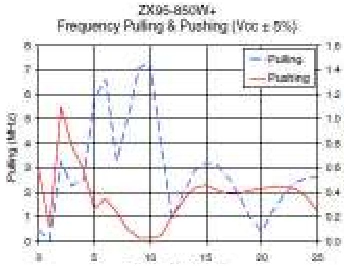
Appendix 2

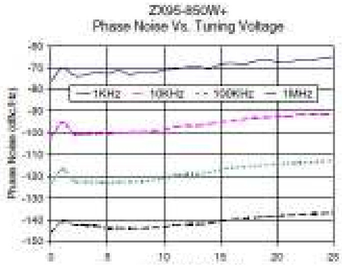
From Data Sheet of VTO ZX 65-850, Mini-Circuits Inc.

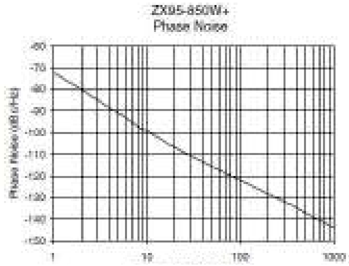

ZX95-850W+
Frequency and Tuning Sensitivity
FREQ. @ -55°C
FREQ. @ +25°C
FREQ. @ +85°C
T.SENS @ +25°C
Frequency (MHz)
Tuning Sensitivity (MHz/V)
Tuning Voltage (V)


ZX95-850W+
Power Output
-55°C
+25°C
+85°C
Output Power (dBm)
Tuning Voltage (V)


ZX95-850W+
Harmonics Level
F2
F3
F4
Harmonics (dBc)
Tuning Voltage (V)


ZX95-850W+
Frequency Pulling & Pushing (Vcc ± 5%)
Pulling
Pushing
Pulling (MHz)
Pushing (MHz/V)


ZX95-850W+
Phase Noise Vs. Tuning Voltage
1KHz
10KHz
100KHz
1MHz
Phase Noise (dBc/Hz)


ZX95-850W+
Phase Noise
Phase Noise (dBc/Hz)