DEVELOPMENT OF UHF SPARK-SWITCHED L-C OSCILLATORS*

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Abstract

Spark switched L-C Oscillator (LCO) transmitters have operated in the Low, Medium, and High Frequency Bands (10's of kHz to 10's of MHz) throughout the history of radio. In the 1970's they were operated in the VHF Band and carefully characterized by Moran, et al [1]. By applying ultra-fast gas switching techniques and by overcomming spark gap losses we have operated LCO transmitters in the UHF (300 MHz to 3 GHz) region. Two minute runs at 1 kHz repetition rate with a peak voltage of 120 kV has been achieved.

UHF oscillators are inherently small because of the low inductance and capacitance required to generate ultra-high frequencies. This size constraint forces the device to operate at very high voltage in order to store enough energy to drive the antenna in spite of series switch losses and parallel corona and stray capacity losses. The spark gap must close in a time short compared to one half an R-F cycle for efficient switching; this equates to a few hundred picoseconds at UHF.

The LCO output is a damped sinusoid of a few cycles duration. While the fractional bandwidth (3-dB bandwidth divided by the center frequency) can be 10% to 80% depending on the Q, it is much smaller than the bandwidth of UWB impulse sources (>100% fractional bandwidth with multi-octave coverage). Compared to UWB, the narrower bandwidth permits the use of higher gain antennas which can efficiently increase the effective radiated power (ERP) over a given frequency range.

We have constructed L-C Oscillators with center frequencies of 450 MHz up to 800 MHz. The Q of these oscillators varies from 6 to 8 for the 450 MHz device, down to 1 to 2 for the 800 MHz unit. Q is increased when a resonant antenna or antenna-reflector combination is added. Prototypes with simple fat-dipole antennas and small parabolic reflectors (8" X 20") have radiated normalized electric field strengths of 60 kV/m @ 1 meter (measured in far-field and extrapolated back to 1 meter).

To obtain maximum effective radiated power, we will mount the LCO, fat dipole, and small parabolic cylinder reflector at the focus of a large (12') parabolic dish. This assembly is currently under construction.

The LCO

The first step in developing the complete transmitter was to achieve UHF operation in an LCO. Advances were required in switching speed and efficiency over the lower frequency predecessors.

The LCO is a self-resonant R-L-C circuit. It consists of two disc shaped parallel plates which form the capacitor and a spark gap switch which penetrates the dielectric between the capacitor plates. Figure 1 shows a cross section of the device. The geometric inductance of the plates and the spark gap determine the value of L. For the 700 MHz oscillator which we will discuss here, C=3.6 pF and L=14 nH. Series resistance is largely determined by the spark gap, and parallel resistance by the antenna load and effective loading by corona. The center frequency of the unloaded oscillator's spectrum is shifted downward by the series and parallel resistive loses. As the R-L-C circuit approaches critical damping, Q lowers, and the spectrum widens and moves downward in frequency. This condition is thoroughly described in [1] and [2]. This frequency shift is significant and becomes a design consideration when the circuit Q is low (say <3).

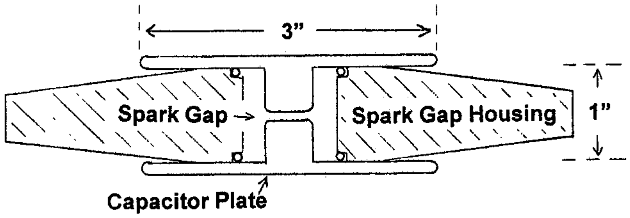
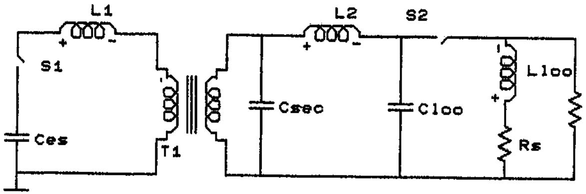


Figure 1. 700 MHz LCO cross-section showing the two capacitor plates, insulator, and switch.

A simple bipolar output modulator charges the LCO. It comprises an energy storage capacitor, thyratron tube switch, and a bipolar pulse transformer with a grounded center tap. The modulator is capable of charging the LCO capacitance, Clco, to 250 kV (+/-125 kV). The circuit for the modulator and LCO is shown schematically in Figure 2, with approximate component values given in the figure.



Ces=energy storage, 12.5nf
S1=Thyratron Tube
L1=Driver Circuit L, 107nh
T1=1:14
Csec=Trans sec stray cap, 60pf
L2=series L (leads)

Clco=3.6pf
Llco=14.2nh
S2=LCO Spark Gap
Rs=Series LCO Losses
Rp=LCO Parallel Load

Figure 2. Modulator-LCO electrical schematic.

Bipolar charging the LCO greatly reduces the energy stored in stray capacitance. Even at that, the effective stray capacity of the transformer secondary, Csec, and connecting leads is some 10's of picofarads. This stray capacity is much larger than the LCO capacitance and must be charged in parallel with the oscillator. This is the largest source of inefficiency in the device.

Ultra-fast switching and high recovery rate are essential for the LCO spark gap. It must turn on in a time short compared to one half cycle at 700 MHz and then recover its dielectric strength before the next recharge begins (<<1 ms). Hydrogen gas was chosen for use in the spark gap. It has been demonstrated to have the fastest turn-on time of any reasonable dielectric gas (some others, e. g. helium, are very fast but have insufficient dielectric strength). Risetimes <100 ps have been measured for hydrogen breakdowns at high electric fields (a few MV/cm) [3]. Even at high pressure hydrogen has a very high recovery rate and can operate in spark gap switches to rep-rates >10,000 pulses per second [4].

For the UHF LCO, spark gap losses are a very serious issue. Even at operating voltages in the 100 kV range, only 10's of millijoules are stored in the LCO's capacitor (3.6 pF). If this energy is drawn upon to heat the spark gap to full conduction (series loss) as well as drive the antenna and other parallel losses, the oscillator's output may be quite low. This problem is remedied by extracting energy from the modulator to heat the spark. When the LCO capacitor is fully charged (peak voltage across the transformer secondary), charging current into the LCO is at zero. If the spark gap fires at this point, only the energy stored in the LCO is available to heat the spark. However, by slightly increasing the charging voltage, the spark gap can fire at the same voltage, but on the rising portion of secondary voltage waveform. At this point charging current is still flowing into the LCO and helps to heat the spark with energy supplied by the modulator. Figure 3 shows the difference between two LCO pulses: first, at peak secondary voltage; second, at the same firing voltage, but while current is still flowing into the LCO. The signals are from a B-dot loop placed near the oscillator. Because of out-of-phase reflections they do not track the true pulse shape, but the difference in power is obvious.

The LCO-Antenna Combination

To produce maximum effective radiated power (ERP), we will use a large (12') parabolic dish with the LCO and a 1/2 wavelength sub-reflector mounted at its focus. A drawing is shown in Figure 4. In developing this package, we first chose a dipole to best match the LCO. Then an optimum sub-reflector was selected which would most efficiently "fill" the large parabolic dish. Finally the LCO, dipole, and sub-reflector will be mounted at the focus of the large dish. The modulator was located directly behind the sub-reflector to minimize charge line length (stray capacity) to the LCO. That position also hides the modulator in the "shadow" of the sub-reflector so as not to cause any additional blockage in front of the dish.

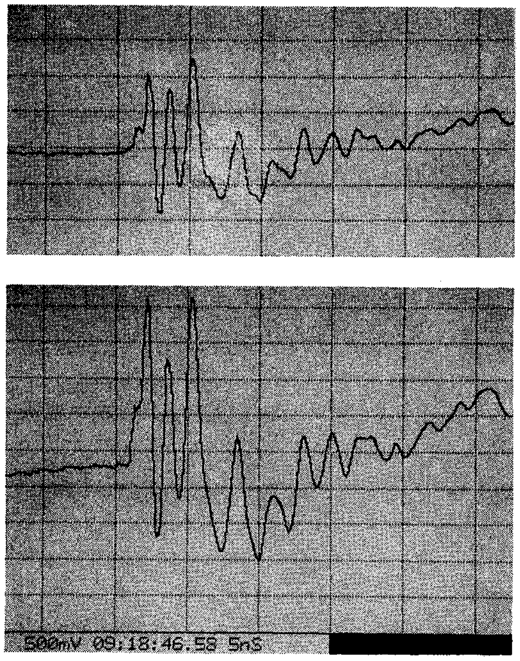


Figure 3. LCO waveforms, equal firing voltage.
A. Firing at peak of charging waveform, current zero.
B. Firing on voltage rise, "current pumping" the spark.

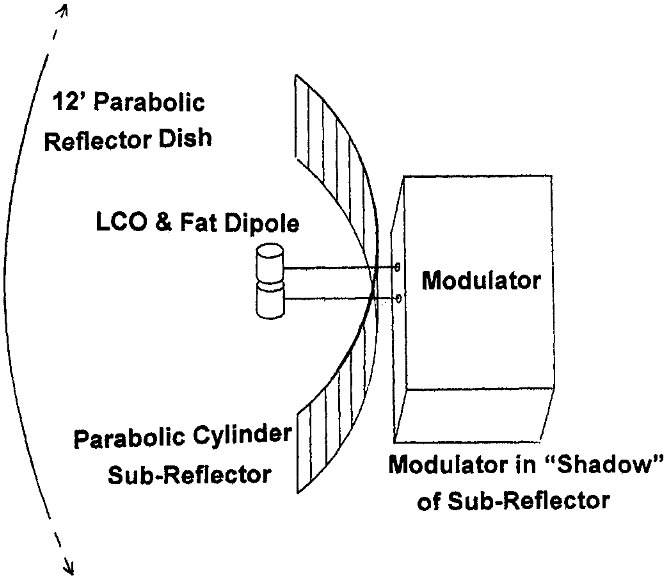


Figure 4. Schematic of the LCO transmitter.

The length to diameter ratio of a dipole affects its bandwidth. Decreasing l/d (a fatter dipole) increases bandwidth. With narrowband continuous wave (CW) signals l/d as high as 200 is considered a fat dipole. For the wideband LCO output we found continuous improvement by decreasing l/d down to 2. At l/d=2, the dipole elements were the same diameter as the LCO capacitor plates and there was no way to attach a fatter antenna. There was practically no change in Q over the range of the data points. Figure 5 is a plot of received peak electric field at constant distance and firing voltage for l/d ranging from 80 (wire dipole) to 2 (3" dia. brass tubing). The span of the E-field data points represents a factor of 15 increase in peak radiated power from l/d=80 to l/d=2. "End effects" became more pronounced as l/d decreased, so the dipole length was reduced from 8" to 6.25" over the range of the data points to maintain half-wave resonance at 700 MHz .

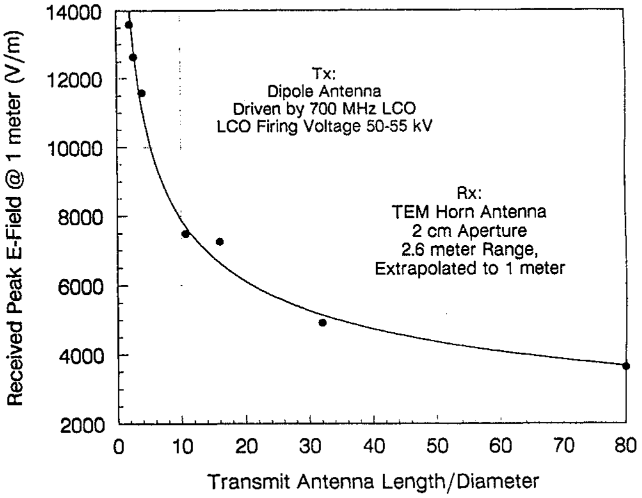


Figure 5. Peak radiated E-field versus dipole length/diameter received in far field and extrapolated to 1 meter range.

The next step in completing the transmitter was to select a sub-reflector for the fat dipole to fill the large parabolic dish efficiently. Properly filling the dish means achieving the most efficient balance between uniform illumination over the entire dish surface, and spillover (energy radiated from the LCO which misses the dish edges and is lost to the sides rather than collimated into the main beam). Our dish is 12 ft. in diameter, has a 54" focal length and f/d=0.4. To best fill this particular dish, a sub-reflector pattern which is 8 to 10 dB down at 60 degrees off boresight is required [5].

For the sub-reflector, we tried flat plane reflectors, 90 degree corners, and parabolic cylinder reflectors. Both solid sheet metal and 1/2" spaced foil strips were tried for each configuration. The difference was practically unmeasurable, so the strip reflectors were chosen because they have lower stray capacity to the LCO. As each reflector was tested we first optimized the distance to the dipole (near 1/4 wavelength) and then rotated the reflector to produce a plot of received E-field versus angle off boresight. These antenna patterns were determined for both the E and H planes of the dipole/sub-reflector set.

Flat reflectors had too broad a pattern; 6 to 7 dB down at 60 degrees off boresight. Corner reflectors had, on the other hand, too narrow a pattern, with a total beamwidth of only 30 degrees on each side of boresight, and large sidelobes. Several styles and sizes of corners were tried. None had an acceptable beamwidth.

Parabolic cylinder reflectors proved superior both in maximum boresight field strength and in optimum beamwidth. We varied the f/d ratio to best satisfy the primary dish filling criteria. E and H plane patterns for an f/d=0.21 parabolic cylinder are shown in Figure 6. Boresight E-field for this antenna is >30 kV/m with the LCO spark gap operating at 70 kV. Both the E and H plane patterns are 10 dB down at 60 degrees. The large back lobe in the antenna pattern consists of low frequency content for which the sub-reflector is inefficient.

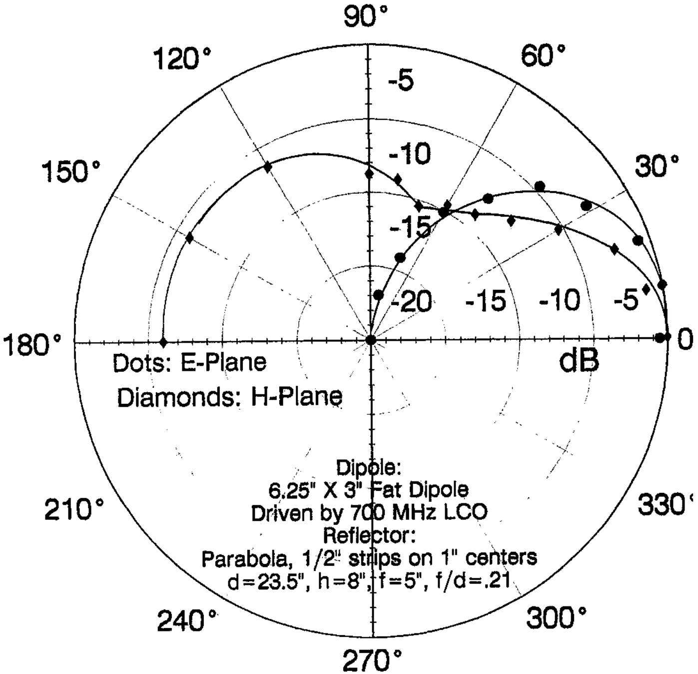


Figure 6. Antenna pattern for 700 MHz LCO with parabolic cylinder sub-reflector. Zero dB equals >30 kV/m @ 1 meter.

Finally, Figure 7 is the received E-field and corresponding frequency spectrum for the LCO and fat dipole with a parabolic sub-reflector. This signal was received by way of a wideband TEM horn having a resistivly loaded aperture and an effective receiving height of 2 cm from 100 MHZ to 2.5 GHz.

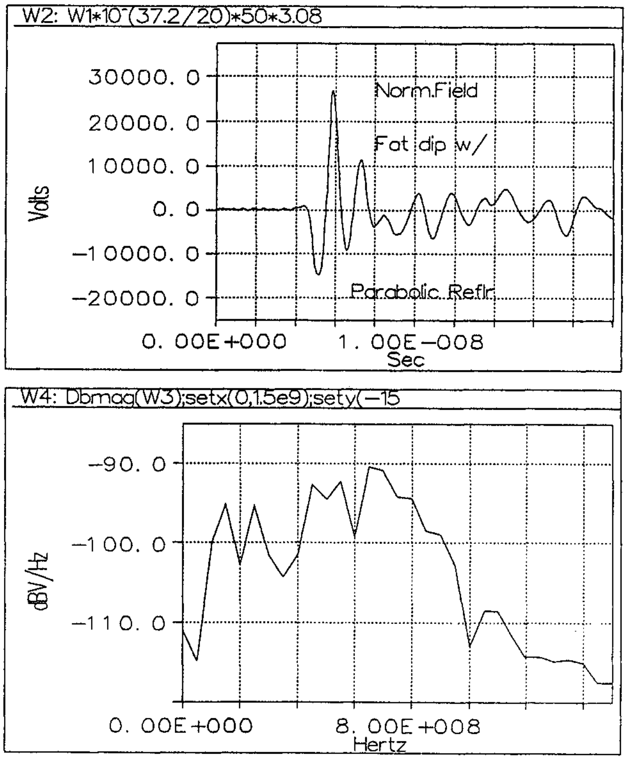


Figure 7. Received E-field and frequency spectrum for the 700 MHz LCO.

Summary

To date, we have developed a UHF LCO with 700 MHz center frequency, a rep-rate modulator, and an optimized dipole and sub-reflector combination. The sub-reflector assembly produces normalized fields of 60 kV/m at an operating voltage of about 120 kV. Rep-rate operation at >70 kV is restricted by air breakdown. To increase the operating voltage, the device was installed in a gas-tight plastic box filled with sulfur hexaflouride gas. The insulating gas allowed doubling the operating voltage. The gas box is now to be mounted at the focus of our 12' parabolic dish for high power testing.

The LCO with its dipole and sub-reflector have operated at 120 kV for two minute run times at 1 kHz rep-rate.

[1] S. L. Moran, "High Repetition Rate L-C Oscillators", Naval Surface Weapons Center Technical Report, NSWC/DL TR-3658, 1977

[2] F. E. Terman, Radio Engineer's Handbook, pp. 145-148, McGraw-Hill, New York, 1943

[3] L. F. Rinehart et. al., "An Enantiomorphic Blumlein Impulse Generator", Conference Record of the Twentieth Power Modulator Symposium, June, 1992

[4] S. L. Moran et. al., "Recovery of Electric Strength in Pressurized Spark Gaps", Proceedings of the Fifteenth Power Modulator Symposium, June, 1982

[5] W. L. Stutzman and G. A. Thiele, Antenna Theory and Design, pp. 433-434, John Wiley & Sons, New York, 1981