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On the Reduction of Detector Diode Losses in a Crystal Radio

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Current design techniques for high-performance crystal radio receivers call for the use of quality components in the RF, detection and AF sections of these radios, together with overall good antenna-ground systems. Sensitive magnetic or piezoelectric headphones, low-loss audio matching transformers and R-C equalization networks, or "bennies", are mandatory in AF ends. RF stages require high-Q coils and low-loss fixed or variable capacitors. Interesting to note here is the fact that varactor diodes are finding widespread use as replacements for capacitors of the variable type in a number of short-wave crystal radio designs. Detector diodes, on the other hand, should be high-quality sensitive types, usually germanium devices optimized for radio frequency operation, i.e., having small reverse currents and improved detection efficiency. Very good performance has been reported [1] employing Schottky-barrier diodes in the detection stages, although these require the use of rather expensive large turns-ratio audio-matching transformers for optimum power transfer to the operator's headphones.

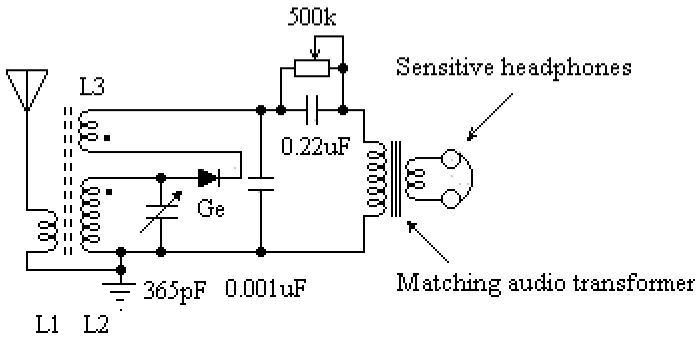
A simple feedback technique using only passive circuit components can improve the efficiency of a cheap low-quality germanium detector diode. For this means, a fraction of the detected RF energy is directed back to the tuned L-C circuit, in phase with the incoming signal, increasing thereby the loaded tank's Q. This subtlety has been recently studied and tested by the author in a ferrite-antenna based simple crystal set, using a number of germanium diodes commonly found in a spare parts box. Experimental results suggest a reduction of detector diode losses, after an improvement of the receiver's tuning characteristics. All tested diodes gave broad tuning responses prior to utilization of feedback, selectivity improving noticeably thereafter.

Fig.1 shows the schematic diagram of the modified crystal receiver employed by the author. A passive feedback loop can be observed to exist in the circuit, that which comprises L_3. This coil, wound over the cold end of L_2, acts as a sort of tickler coil, feeding back to the tuning tank RF-detected currents of the same frequency and phase as those induced by the incoming wave. An equivalent circuit for carrier frequencies is shown in Fig.2, where $v_A(t)$ and $v_K(t)$ are the diode's anode and cathode potentials to ground, respectively.

Shockley's diode equation states:

$$i_D = I_S\left(e^{\frac{v_D}{nV_T}} - 1\right) \qquad \ldots(1)$$

where i_D is the diode's current in amperes, v_D is the diode's anode-cathode voltage drop in volts, I_S is the inverse saturation current in amperes, n is the diode's ideality factor and V_T is 0.026 Volts. I_S is a scale factor, such that if we wish i_D in microamperes, for example, we need only put I_S in these same units.



L1 = 4 turns - 1cm from L2's cold end
L2 = 240uH
L3 = 1/6 of the number of turns of L2

Wind L3 over L2's cold end.
Connect L3 as to enhance selectivity.
All coils wound on a suitable ferrite rod

Fig. 1 Crystal set with enhanced selectivity

Eq.(1) may be expanded into a Taylor's series:

$$i_D = A_0 + A_1 v_D + A_2 v_D^{\ 2} + A_3 v_D^{\ 3} + \ldots \qquad \ldots(2)$$

where

$$v_D = v_A(t) - v_K(t) \qquad \ldots(3)$$

and A_0, A_1, A_2, A_3, ... are constants having the values:

$$A_0 = 0$$

$$A_1 = \frac{I_S}{nV_T}$$

$$A_2 = \frac{I_S}{(nV_T)^2} \cdot \frac{1}{2!}$$

$$A_3 = \frac{I_S}{(nV_T)^3} \cdot \frac{1}{3!}$$

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Coefficient A_1 is responsible for the tuning tank's RF loading at the carrier's frequency and is equal to the diode's conductance at $v_D = 0$, or zero-crossing conductance. On the other hand, coefficient A_2 is responsible for the square-law AM demodulation of the incoming RF signal.

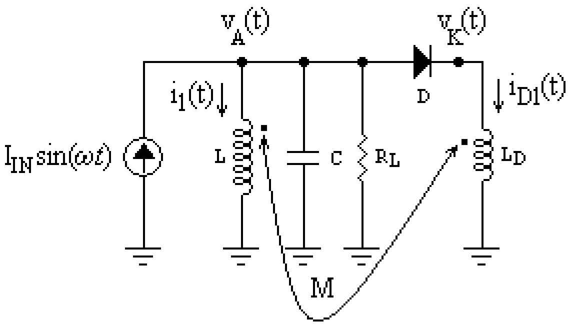

Fig.2 Equivalent circuit at carrier frequencies

In Fig.2, $I_{IN}\ sin(\omega t)$ is the RF signal current induced by the passing radio wave and driving the tuning tank. Resistor R_L represents the tuned circuit's parallel RF losses. M is the mutual inductance existing between coils L and L_D (L and L_D represent L_2 and L_3, respectively). We are interested in the fundamental frequency component of the diode's current, i.e., the carrier-frequency component $i_{D1}(t)$. Thus, we may write:

$$i_{D1}(t) = A_1 v_D = A_1\left[v_A(t) - v_K(t)\right] \qquad \ldots(4)$$

In the frequency domain:

$$I_{D1}(j\omega) = A_1 V_A(j\omega) - A_1 V_K(j\omega) \qquad \ldots(5)$$

From Fig.2:

$$I_{IN}(j\omega) = I_1(j\omega) + V_A(j\omega)\cdot\left(j\omega C + \frac{1}{R_L}\right) + I_{D1}(j\omega) \qquad \ldots(6)$$

$$V_A(j\omega) = I_1(j\omega)\cdot j\omega L + I_{D1}(j\omega)\cdot j\omega M \qquad \ldots(7)$$

and:

$$V_K(j\omega) = I_{D1}(j\omega)\cdot j\omega L_D + I_1(j\omega)\cdot j\omega M \qquad \ldots(8)$$

Substituting Eqs.(7) and (8) in (5):

$$I_{D1}(j\omega) = A_1 I_1(j\omega)\cdot j\omega L + A_1 I_{D1}(j\omega)\cdot j\omega M - A_1 I_{D1}(j\omega)\cdot j\omega L_D - A_1 I_1(j\omega)\cdot j\omega M$$

$$= A_1 I_1(j\omega)\cdot j\omega(L - M) + A_1 I_{D1}(j\omega)\cdot j\omega(M - L_D)$$

Then:

$$I_{D1}(j\omega)\cdot[1-A_1 j\omega(M-L_D)]=A_1 I_1(j\omega)\cdot j\omega(L-M)$$

and

$$I_{D1}(j\omega)=\frac{A_1 I_1(j\omega)\cdot j\omega(L-M)}{1-A_1 j\omega(M-L_D)} \qquad \ldots(9)$$

Substituting for $I_{D1}(j\omega)$ in Eq.(7):

$$V_A(j\omega)=I_1(j\omega)\cdot j\omega L+\frac{A_1 I_1(j\omega)\cdot j\omega(L-M)j\omega M}{1-A_1 j\omega(M-L_D)}$$

$$=I_1(j\omega)\cdot j\omega L-\frac{A_1 I_1(j\omega)\cdot \omega^2(L-M)M}{1-A_1 j\omega(M-L_D)}$$

$$=I_1(j\omega)\cdot\frac{A_1\omega^2\left(M^2-LL_D\right)+j\omega L}{1-A_1 j\omega(M-L_D)}$$

$$=I_1(j\omega)\cdot\frac{A_1\omega^2 LL_D\left(k^2-1\right)+j\omega L}{1-A_1 j\omega(M-L_D)}$$

where $M^2=k^2LL_D$ and $k=$ coupling coefficient between L and L_D.

Then:

$$I_1(j\omega)=V_A(j\omega)\cdot\frac{[1-A_1 j\omega(M-L_D)]}{A_1\omega^2 LL_D\left(k^2-1\right)+j\omega L} \qquad \ldots(10)$$

Substituting in Eq.(9):

$$I_{D1}(j\omega)=V_A(j\omega)\cdot\frac{A_1 j\omega(L-M)}{A_1\omega^2 LL_D\left(k^2-1\right)+j\omega L} \qquad \ldots(11)$$

If $A_1\omega L_D\left(1-k^2\right)<<1$ then:

$$I_1(j\omega)=V_A(j\omega)\cdot\frac{[1-A_1 j\omega(M-L_D)]}{j\omega L} \qquad \ldots(12)$$

Eq.(11) reduces to:

$$I_{D1}(j\omega)=V_A(j\omega)\cdot A_1\left(1-\frac{M}{L}\right) \qquad \ldots(13)$$

Comparison with Eq.(5) yields:

$$V_K(j\omega) = V_A(j\omega)\cdot\frac{M}{L} \qquad \ldots(14)$$

Substituting Eqs.(12) and (13) in Eq.(6):

$$I_{IN}(j\omega) = V_A(j\omega)\cdot\frac{[1 - A_1 j\omega(M - L_D)]}{j\omega L} + V_A(j\omega)\cdot\left(j\omega C + \frac{1}{R_L}\right) + V_A(j\omega)\cdot A_1\left(1 - \frac{M}{L}\right)$$

$$= V_A(j\omega)\cdot\frac{\left(1-\omega^2 LC\right) + j\omega L\left[A_1\left(1-\frac{M}{L}\right) + \frac{1}{R_L} - \frac{A_1(M - L_D)}{L}\right]}{j\omega L}$$

At resonance:

$$1 - \omega^2 LC = 0$$

which yields:

$$\omega_R = \frac{1}{\sqrt{LC}} \qquad \ldots(15)$$

The tune circuit's admittance at ω_R is:

$$Y(j\omega_R) = \frac{I_{IN}(j\omega_R)}{V_A(j\omega_R)} = A_1\left(1-\frac{M}{L}\right) + \frac{1}{R_L} - A_1\left(\frac{M - L_D}{L}\right)$$

$$= A_1\left(1 - 2\frac{M}{L} + \frac{L_D}{L}\right) + \frac{1}{R_L}$$

$$= A_1\left(1 - 2k\sqrt{\frac{L_D}{L}} + \frac{L_D}{L}\right) + \frac{1}{R_L}$$

If $k \approx 1$:

$$Y(j\omega_R) = G(\omega_R) \approx A_1\left(1 - \sqrt{\frac{L_D}{L}}\right)^2 + \frac{1}{R_L} \qquad \ldots(16)$$

The diode's conductance at resonance is then:

$$G_D = A_1\left(1-\sqrt{\frac{L_D}{L}}\right)^2 \qquad \ldots(17)$$

A smaller G_D means reduced parallel losses in the tuned circuit due to the diode's zero-crossing resistance value.

We conclude that passive positive feedback in the crystal receiver acts reducing detector diode losses by a factor $\left(1-\sqrt{\frac{L_D}{L}}\right)^2$ and, within the range of frequencies for which the equivalent model is valid, it won´t change the tuned circuit's resonance radian frequency $\omega_R = \frac{1}{\sqrt{LC}}$.

References

[1] *Tongue, Ben. Crystal Radio Set Systems: Design, Measurement and Improvement-- Practical considerations, helpful definitions of terms and useful explanations of some concepts used in this site.*

http://www.bentongue.com/xtalset/0def_exp/0def_exp.html (seen on May 10th 2009)

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