

Physical Principles and Performance Analysis of the Frequency Selection Mechanism in Crystal Radios

Ma Yuqi

Suzhou High School of Jiangsu Province, Jiangsu, Suzhou, 215007, China

Keywords: Crystal radio; Frequency selection; LC resonance; Quality factor; Detector loading

Abstract: A crystal radio provides a compact passive platform for examining how weak radio-frequency energy is captured, selected, rectified and converted into audible sound without external amplification. Focusing on the frequency selection mechanism of the receiver, the analysis links antenna coupling, LC resonance, quality factor, detector loading and adjacent-channel rejection within a single signal path. The resonant frequency is determined by the inductance-capacitance combination, while the actual tuning response is reshaped by coil resistance, stray capacitance, diode conduction and earphone impedance. Calculated LC data and load-condition comparison show that higher quality factors narrow the passband and strengthen station separation, whereas heavier detector or audio loading increases damping and reduces selectivity. The results indicate that the performance of a crystal radio depends on a careful balance between signal strength and resonance sharpness. Practical improvement should focus on low-loss coil construction, stable variable capacitance, controlled antenna coupling, low-threshold detection and high-impedance audio loading, so that passive reception can maintain sufficient sensitivity while preserving clear frequency discrimination.

1. Introduction

A crystal radio appears simple at first sight, yet its operating process contains several core problems of radio-frequency engineering. A wire antenna gathers only a small amount of electromagnetic energy from the surrounding field, and every later stage must share this limited energy with little tolerance for loss. The tuning coil and variable capacitor decide which carrier is allowed to dominate the circuit voltage, while the detector and earphone immediately change that condition by drawing energy from the same resonant network. Clear reception therefore depends on a delicate balance: stronger antenna coupling may raise the signal level but flatten the resonance curve; a sharper LC response may separate nearby stations more clearly but leave less margin for weak-signal detection. These interactions make the crystal radio a useful object for analyzing resonance tuning, impedance loading and passive signal recovery in a visible, measurable and experimentally accessible form^[1].

2. Passive Signal Chain

2.1 Antenna Energy Input

In a crystal radio, the antenna acts as the only entrance for external radio-frequency energy, and its role extends beyond simple signal capture. The incoming electromagnetic wave induces a weak alternating voltage along the antenna conductor, while the grounding path provides a reference potential and completes the receiving system's energy exchange with the surrounding field. Antenna length, height, grounding resistance and nearby conductive objects all influence the available input voltage, yet stronger coupling does not always lead to better reception because direct and heavy antenna loading may draw energy away from the tuned circuit and broaden the later resonance response.

2.2 Tuned Circuit Boundary

The tuned circuit forms the frequency-selective core of the receiver, separating one carrier from other broadcast signals before detection occurs^[2]. The coil and variable capacitor store energy alternately in magnetic and electric fields, and their combined values determine the frequency at which the circuit produces its strongest voltage response. The detector diode and earphone belong to the following recovery stage, but they remain electrically connected to the resonant network, so their conduction state and impedance condition reshape the actual tuning curve rather than remaining passive observers after selection.

2.3 Load Energy Sharing

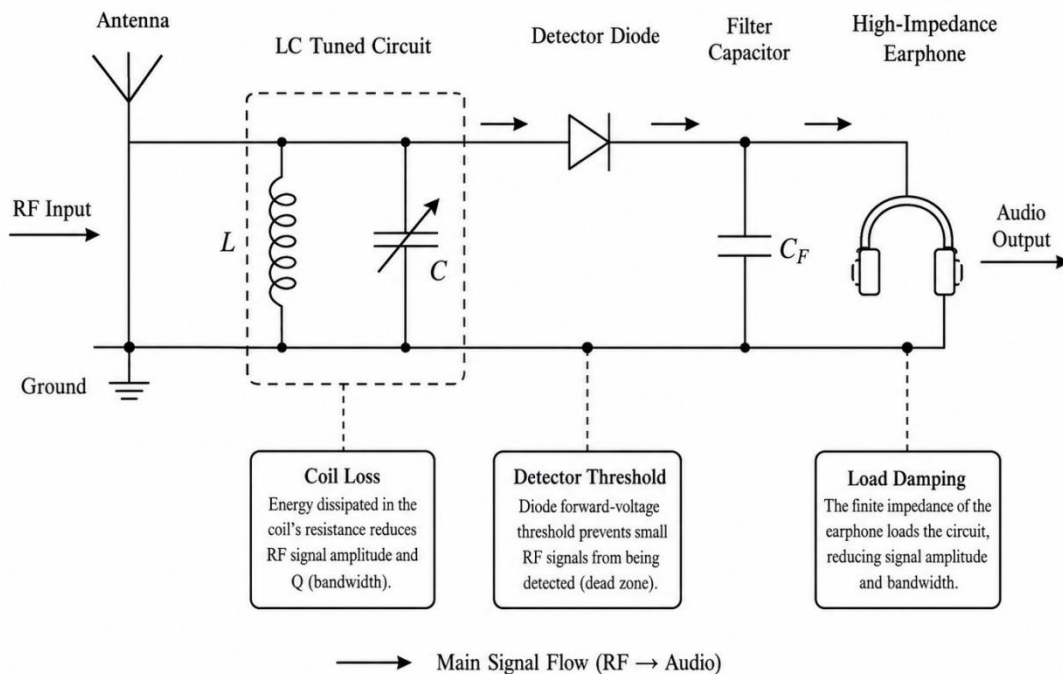


Figure 1. Signal Flow and Energy Distribution in a Crystal Radio

The passive nature of a crystal radio makes energy allocation more critical than in powered receivers because no amplifier restores signal loss after tuning. Coil resistance, dielectric leakage, diode threshold voltage, contact instability and earphone impedance all consume part of the

captured energy, leaving only a limited portion for audible output^[3]. A lower audio load may increase current in the earphone, yet it also introduces heavier damping into the resonant circuit, while a high-impedance load preserves a sharper tuning peak and usually supports clearer station separation under weak-signal conditions, as shown in Figure 1.

3. LC Selection Physics

3.1 Resonance Sets Channel

Frequency selection in a crystal radio begins with the voltage response of the LC tuned circuit, where the coil inductance L and the tuning capacitance C determine the carrier frequency that receives the strongest reinforcement. The resonant point is expressed as

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

where f_0 is the resonant frequency in hertz, L is measured in henries, and C is measured in farads. When the incoming AM carrier approaches f_0 , magnetic-field energy in the coil and electric-field energy in the capacitor exchange periodically, causing the voltage across the tuned circuit to rise above off-resonance signals. As listed in Table 1, a 240 μH coil combined with a 365–35 pF tuning capacitor covers most of the medium-wave broadcast range, and the tuning knob therefore acts as a frequency-positioning device rather than a simple volume control^[3].

Table 1. Calculated Resonant Frequencies under Different LC Values

No.	Inductance L/ μH	Capacitance C/pF	Calculated Frequency/kHz	Tuning Position
1	240	365	537	Lower AM band
2	240	220	693	Low-middle band
3	240	100	1027	Middle band
4	240	50	1453	Upper band
5	240	35	1737	Upper boundary

3.2 Q Factor Defines Bandwidth

The sharpness of frequency selection is governed by the quality factor Q , which links the resonant frequency to the half-power bandwidth Δf :

$$Q = \frac{f_0}{\Delta f}$$

A circuit tuned to 1000 kHz with $Q = 100$ has an approximate bandwidth of 10 kHz, while the same circuit with $Q = 40$ expands to about 25 kHz and admits more adjacent-channel energy. In practical AM reception, a narrow response improves station separation, yet excessive narrowing may reduce recovered audio clarity because sideband components around the carrier also carry speech and music information. Figure 2 should therefore present high- Q , medium- Q and low- Q resonance curves on the same frequency axis, showing how bandwidth expansion lowers peak selectivity and increases overlap between nearby carriers^[4].

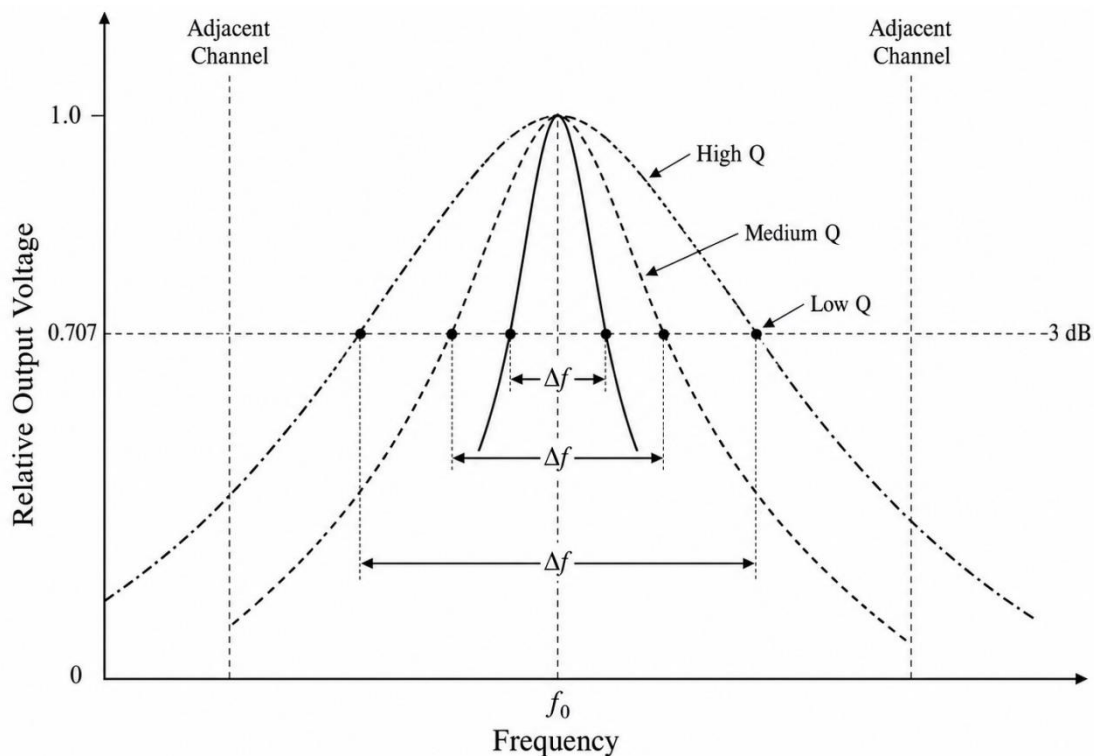


Figure 2. Resonance Curves under Different Q Values

Figure 2 should show three black-and-white resonance curves labeled High Q, Medium Q and Low Q, with f_0 , Δf , -3 dB bandwidth and adjacent-channel positions marked clearly.

3.3 Coupling Reshapes Selectivity

The theoretical tuning curve changes once the antenna, detector and earphone are connected to the resonant network^[5]. A long antenna may deliver a higher RF voltage, but its equivalent resistance and capacitance add external damping to the LC circuit, lowering the loaded Q and flattening the voltage peak. The detector diode also draws current during conduction, and a low-impedance audio load accelerates energy removal from the tank circuit, causing wider bandwidth and weaker adjacent-channel rejection. A more stable design normally uses antenna tap coupling, small-capacitance coupling or a separate link coil, while the detector side benefits from a low-threshold diode and a high-impedance earphone so that frequency discrimination remains sharper under weak-signal conditions^[6].

4. Performance Modelling

4.1 Tuning Range and Error

Performance evaluation should first verify whether the tuned circuit covers the intended AM broadcast range with acceptable frequency deviation^[7]. For a receiver using a $240 \mu\text{H}$ coil and a $365\text{--}35 \text{ pF}$ variable capacitor, the calculated range extends from about 537 kHz to 1737 kHz , which is sufficient for most medium-wave reception. In practical adjustment, the measured resonance peak often shifts lower than the calculated value because the coil has distributed capacitance and the wiring introduces stray capacitance of several picofarads. A test procedure may inject a fixed RF signal from 600 kHz to 1600 kHz in 100 kHz steps, then record the capacitor position at the

strongest detector output. If the deviation remains within 3%–5%, the tuning network is generally stable enough for manual station selection, while larger error usually indicates excessive lead length, unstable coil geometry or parasitic coupling near the tuning capacitor.

4.2 Load Damping and Sensitivity

The sensitivity of a crystal radio is strongly influenced by the load connected after the detector because the receiver has no active gain stage to compensate for energy loss. Under a fixed test condition, such as $f_0=1000$ kHz, $L=240$ μ H and constant RF input amplitude, decreasing the load resistance raises the detected audio current but lowers the loaded quality factor. As shown in Table 2, reducing the load from 100 k Ω to 10 k Ω increases the relative audio output from 0.72 to 1.00, yet the effective Q falls from 82 to 22 and the bandwidth expands from 12.2 kHz to 45.5 kHz. This means louder reception may come at the cost of poorer station separation. A high-impedance earphone, low-threshold germanium or Schottky detector, and small filter capacitance are more suitable for weak-signal reception because they reduce extraction loss from the LC tank while maintaining usable audio voltage.

Table 2. Performance under Different Load Conditions

Load Condition	Load Resistance/k Ω	Effective Q	Bandwidth/kHz	Relative Audio Output	Adjacent Rejection/dB
Unloaded tuned circuit	∞	145	6.9	—	-28
High-impedance earphone	100	82	12.2	0.72	-21
Standard detector load	47	55	18.2	0.90	-14
Low-resistance load	10	22	45.5	1.00	-7

4.3 Rejection and Distortion

Adjacent-channel rejection should be evaluated together with audio recovery, since a receiver that produces stronger sound may still perform poorly when nearby carriers enter the detector. In practical testing, the output at the tuned carrier may be taken as the reference, and the residual output at an adjacent frequency offset, such as ± 10 kHz or ± 20 kHz in the AM band, can be recorded as a rejection value in dB under the same RF input amplitude. The data in Table 2 show that heavier loading weakens rejection from -21 dB to -7 dB, which means that the low-resistance load allows more off-frequency energy to pass through the detector and makes the receiver more vulnerable to station overlap when two transmitters are close in frequency. Audio distortion should also be checked during the same test, because the detector does not simply “turn RF into sound”, but follows the envelope only when the diode conduction point, filter capacitance and load resistance remain within a suitable range. If the detector operates near its threshold, weak carrier peaks are clipped and low-level speech details become unstable, while an oversized filter capacitor may smooth the envelope too heavily and reduce articulation in higher audio components. For a 1 MHz carrier with ordinary speech modulation, the filter path should suppress RF residue while still following audio variation, so the selected capacitance must be judged together with a 47–100 k Ω load rather than chosen in isolation. A practical design should rank performance in three steps: the

signal must first be detectable at low input voltage, adjacent stations must remain separated at the tuned point, and the recovered envelope should retain intelligible speech without excessive background mixing or dull high-frequency response^[8].

5. Conclusion

The frequency selection performance of a crystal radio depends on the interaction between LC resonance and passive loading. The coil-capacitor network defines the tuned carrier frequency, while the loaded quality factor determines bandwidth, adjacent-channel rejection and tuning sharpness. Practical performance cannot be judged from calculated L and C values alone, because antenna coupling, coil loss, detector threshold, stray capacitance and earphone impedance reshape the actual response. A reliable design should use low-loss winding, stable capacitance, controlled antenna coupling and high-impedance audio loading. These measures help preserve sensitivity while maintaining clear station separation in passive AM reception.

References

- [1] Shi Z, Zhao Y, Liao Y, et al. Reversible and Dynamic Tuning Mechanism for Fabry–Pérot Polaritonic Resonators[J]. *Nanophotonics*, 2026, 15(8):e70074.
- [2] Cheng R, Cao Z, Lin J, et al. Investigation of the tuning mechanism in a pump-induced tunable Lyot filter and its applications.[J].*Optics express*,2026,34(6):11411-11420.
- [3] Wang X, Xia E, Wang C, et al. Active Wavelength Control of Fiber Bragg Gratings: A Systematic Review of Tuning Mechanisms, Emerging Applications, and Future Frontiers[J].*Micromachines*,2026,17(2):263.
- [4] Röhlig D, Laude V, Zichner R, et al. Radio wave attenuation by a large-scale photonic crystal sculpture[J].*Scientific Reports*, 2025,15(1):12317.
- [5] Amarloo H, Noaman M, Yu P S, et al. A photonic crystal receiver for Rydberg atom-based sensing[J]. *Communications Engineering*, 2025,4(1):70.
- [6] Jianying C, Hengyu Z, Hui J, et al. Origami tunable frequency selective fabric and its tuning mechanism[J]. *Composites Part A*, 2023, 164
- [7] DongGyu L, Joonchul S, Soo H K, et al. Autonomous Resonance-Tuning Mechanism for Environmental Adaptive Energy Harvesting[J]. *Advanced Science*,2022,10(3):e2205179.
- [8] Janice L W, Sungjae H, Ki-Tae K, et al. Van der Waals crystal radio with Pt/MoSe₂ Schottky diode and h-BN capacitor for RF energy harvesting[J]. *Nano Energy*,2022,92