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DESIGN OF A CASCODE BIPOLAR JUNCTION TRANSISTOR (BJT) RADIO FREQUENCY (RF) AMPLIFIER CIRCUIT

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Abstrak

Artikel ini mempresentasikan tentang sebuah penelitian untuk mengembangkan suatu rangkaian penguat penerima RF BJT audio. Penguat RF yang dibuat tersusun dari sebuah rangkaian penguat *cascode* $CE - CB$ yang diubah menjadi penguat RF dengan cara menambahkan dua buah rangkaian *resonator* parallel. Satu rangkaian resonator paralel LC ditempatkan pada bagian input dan satu lagi rangkaian resonator paralel LC digunakan sebagai beban collector. Rangkaian resonator paralel LC dimanfaatkan karena rangkaian ini akan digunakan hanya untuk rentang frekuensi yang sempit. Frekuensi penguat RF ini disetel pada $\cong 734\ kHz$. Sebuah *spoiling resistor* sebesar $125.7\ \Omega$ ditambahkan secara seri ke komponen induktor di rangkaian *tuned* untuk mengurangi ketajaman dari puncak resonansi, sehingga bisa menghasilkan *bandwidth* sebesar $20\ kHz$. Konfigurasi *cascode* digunakan untuk memperbaiki performansi penguat RF ini pada frekuensi tinggi. Simulasi *Multisim* yang dihasilkan dari rangkaian menunjukkan bahwa rangkaian ini bisa berfungsi sesuai dengan spesifikasi. Bisa disimpulkan bahwa rangkaian yang didesain berhasil menguatkan hanya sinyal dengan frekuensi dan *bandwidth* yang diinginkan. Yaitu dari frekuensi bawah sebesar $718.246\ kHz$ sampai dengan frekuensi atas sebesar $739.012\ kHz$, dan menolak frekuensi lain yang tidak diinginkan. Jadi, memberikan penguat ini sebuah bandwidth sebesar $20.766\ kHz$. Tegangan puncak dicapai pada frekuensi $729.30\ kHz$. Selanjutnya, konfigurasi *cascode* berhasil menghilangkan penyebab utama dari *high-frequency loss* – yaitu kapasitansi input *Miller*.

Kata kunci: penguat RF, konfigurasi cascode, common emitter, common base, resonator, rangkaian tuned

Abstract

The purpose of this research is to develop an audio BJT RF receiver amplifier circuit. The RF amplifier consists of a cascode $CE - CB$ amplifier which is turned into an RF amplifier by adding two parallel LC resonators. One parallel LC resonator is placed at the input. Another parallel LC circuit is used as a collector load. Parallel LC circuit was employed because this device is intended for use only over a narrow frequency range. The tuned amplifier's frequency was $\cong 734\ kHz$. A spoiling resistor of magnitude $125.7\ \Omega$ was added in series with the tuned circuit's inductor to reduce the sharpness of the resonant peak, resulting in a $20\ kHz$ bandwidth. The famous cascode configuration was employed to improve the high-frequency performance of this RF amplifier. The Multisim simulation results of the circuit shows that it has performed according to the specification. It can be concluded that the designed circuit has successfully carried out his duty, in that only the frequencies of interest within the bandwidth are amplified. The circuit has been able to selects a particular range of frequencies (from a lower frequency of $718.246\ kHz$ up to an upper frequency of $739.012\ kHz$), and rejects the other undesired frequencies. Thus, giving the tuned amplifier a bandwidth of $20.766\ kHz$. The peak voltage was achieved at frequency of $729.30\ kHz$. Furthermore, the cascode configuration employed has effectively eliminates the most trouble source of high-frequency loss – the input Miller capacitance.

Keywords: RF amplifier, cascode configuration, common emitter, common base, resonators, tuned amplifier

1. Introduction

Wireless system and circuit design is one of the most interesting fields in electrical engineering. From the economic point of view, wireless applications can be categorized into cellular/smart phones, cordless phones, wireless data networks, sensor networks, global positioning systems, AM/FM radio, and digital television broadcasting (terrestrial or satellite based). From the engineering point of view, the design of wireless systems has different levels of abstraction which are relevant to radio frequency (RF) antennas, wave propagation phenomena, RF and microwave circuit design, evaluation of noise and intermodulation phenomena, digital modulation, coding, and digital signal processing [1].

Radio Frequency represents the oscillation rate of electromagnetic waves. RF can refer to frequencies as high as $300\,GHz$, or as low as $30\,kHz$. Figure 1 shows approximate frequency ranges for the most commonly encountered portion of the spectrum [2].

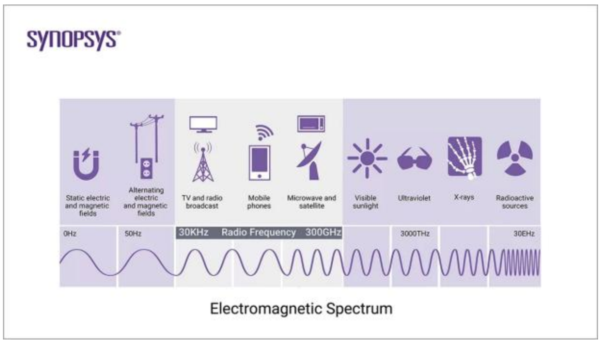

Figure 1. Electromagnetic Spectrum

By definition, Radio Frequency circuit design is a discipline that focuses on the creation of circuits that operate in those radio frequencies.

There are a lot of research have been conducted about this RF circuit design. Some of which can be mentioned as follows. First, there is a research done by H. Fouad, titled "An RF cascode BJT-LNA with shunt-series input matching". In this research, an RF low noise amplifier (LNA) is proposed using BJT cascode topology to provide gain with low bias current consequently lower power dissipation and lower noise figure (NF) [3]. Next, M. M. Joshi, R. Mathew, P. Sarkar, A. Dutt, S. Tiwari and P. Nigam elucidate the design of an LNA for optimizing its gain, noise figure and stability factor with different transistor configurations in the frequency range of 5-6 GHz in their research titled "Performance Analysis of Radio Frequency (RF) Low Noise Amplifier (LNA) with various Transistor Configurations" [4]. And also another research done by H. Fouad, K. Sharaf, E. El-Diwany and H. El-Hennawy presented A simulation comparison of MOSFETs low noise amplifier (LNA) versus BJT LNA is proposed using a PSpice simulator [5]. Another research done by K. I. Arafa, I. L. Abdalla, M. F. Ibrahim and F. A. Farag titled "Design RF cascode amplifier based on the universal gm/ID MOST model by using shifting technique," introduces a new methodology for designing a robust Radio Frequency (RF) amplifier [6].

In this research, an RF BJT amplifier circuit has been designed. The design was done using Multisim industry standard SPICE simulation and circuit design software. The amplifier circuit was built based on the famous cascode $CE-CB$ configuration using BJT transistors. Cascode connections used in this research are often used as the gain elements in amplifier stages when the Miller effect is an issue [7]. The tuned amplifier has a tuned frequency of approximately 734 kHz and a bandwidth of $20\,kHz$.

2. Generic Transceivers

A generic wireless transceiver consists of a transmitter, a receiver and the air air-channel as illustrated in Fig. 2. The transmitter comprises the data source, a signal coder, the RF transmitter front-end and an antenna. In complementary order, the receiver involves an antenna, an RF receiver front-end, a signal decoder and finally the data interface [8].

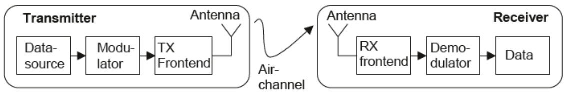

Figure 2. Schematic of Generic Transceiver, TX: Transmitter, RX: Receiver.

Within an RF transceiver, the RF stage takes weak signals within the frequency band received at the antenna and boosts the signals to usable levels.

Starting with the antenna, the performance of the circuit relies on bandpass filters at the antenna to reject any out-of-band noise. At this point, the signal remains very small and stays within the microwatt range. A pre-amplifier or low-noise amplifier (LNA) provides the gain needed for the signal to become usable at the receiver.

3. RF Circuit Design Goals

An RF circuit is a special type of analog circuit operating at RF frequencies that enable signal propagation. However, RF circuit design goals are different from baseband or analog circuits. An RF circuit is a bandpass circuit. For example, consider a simple RF circuit with a transmitter and receiver. The transmitter and receiver handle both baseband (e.g. Audio Frequency) signals and RF signals (bandpass signals). The transmitter input and receiver output belong to baseband frequency, whereas the transmitter output and receiver input correspond to RF signals (bandpass signals) [9].

The design goals of the baseband section and RF section of the transmitter are entirely different from each other. The baseband section of the transmitter aims to achieve a specified power to transmit, whereas the RF section focuses on not interfering with the transceivers operating on adjacent channels. Similarly, the goals of the receiver baseband and RF sections are the recovery of small signals and rejecting the interferences from undesired channels, respectively [9].

4. Resonant Circuits

When capacitors are combined with inductors or are used in special circuits called active filters, it is possible to make circuits that have very sharp frequency characteristics (e.g., a large peak in the response at a particular frequency), compared with the gradual characteristics of the RC filters. These circuits find applications in various audio and RF devices [10].

4.1. Parallel LC Circuits

Parallel LC circuit of Fig. 3 will be used for the bandpass circuit. A parallel LC resonant circuits will be used because this device is intended for use only over a narrow frequency range.

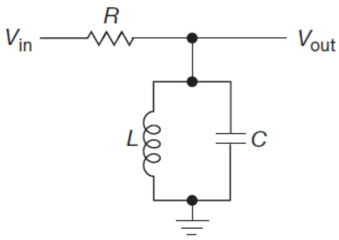

Figure 3. LC Resonant Circuit: Bandpass Filter

The impedance of the LC combination at frequency f is just as follows:

$$\frac{1}{\boldsymbol{Z}_{LC}} = \frac{1}{\boldsymbol{Z}_L} + \frac{1}{\boldsymbol{Z}_C} = \frac{1}{j\omega L} - \frac{\omega C}{j} = j\left(\omega C - \frac{1}{\omega L}\right)$$

i.e.

$$\boldsymbol{Z}_{LC} = \frac{j}{(1/\omega L) - \omega C}$$

In combination with resistor R it forms a voltage divider. Because of the opposite behaviour of inductors and capacitors, the impedance of the parallel LC goes to infinity at the *resonant frequency*

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

$\left(i.e.\ \omega_0 = 2\pi f_0 = \frac{1}{\sqrt{LC}}\right)$, giving a peak response there. The overall response is as shown in Figure 4.

The main role of an LC resonator is to provide a physical realization of a sinusoidal function, which is fundamental for wireless radio communications, and therefore for radio transceiver circuit design.

A $Q-$ spoiling resistor is sometimes added intentionally to reduce the sharpness of the resonant peak. This circuit is also known as a "tuned circuit," or "tank" and is used extensively in RF circuits to select a particular frequency for amplification (the L or C can be variable, so that the resonant frequency can be tuned). The *quality factor* Q is a measure of the sharpness of the peak. It equals the resonant frequency divided by the width at the -3 dB points. For a parallel RLC circuit, $Q = \omega_0 RC$.

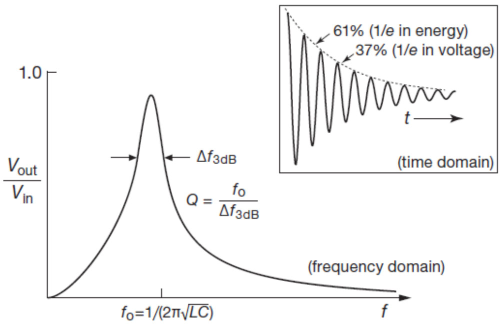

Figure 4. Frequency Response of Parallel LC "tank" Circuit. The Inset Shows the Time-Domain Behavior: a Damped Oscillation ("ringing") Waveform Following an Input Voltage Step or Pulse.

5. Design of a Single Stage Common-Emitter Voltage Amplifier

Figure 5 shows a discrete-circuit amplifier with a common-emitter (CE) configuration. This single-stage CE amplifier will act as an audio frequency amplifier (the baseband section, whose frequencies are audible to average human, which are 20 to 20,000 Hz).

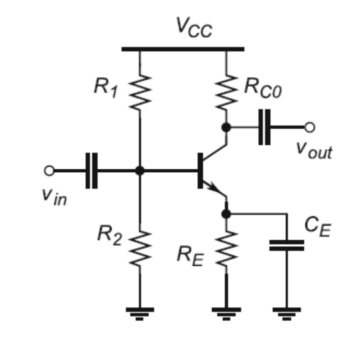

Figure 5. Voltage Divider Biasing Network for a CE Amplifier with a Capacitive Input Signal and Output Signal Coupling

In principle, later on, this single-stage CE amplifier can be easily turned into a CE RF amplifier with the following modifications: first the collector's resistive load R_{C0} is replaced by a resonant circuit (the parallel LC "tank" circuit) , and then another parallel LC "tank" circuit is added between the input node and the ground.

To determine the characteristic parameters of the CE amplifier above (especially the amplifier input impedance), we replace the BJT with its hybrid-π model, substitute V_{CC} with a short circuit to ground, and replace the coupling and bypass capacitors with short circuits. The small-signal equivalent circuit produced of the CE amplifier is shown in Fig. 6 below. The analysis is given in the figure [11].

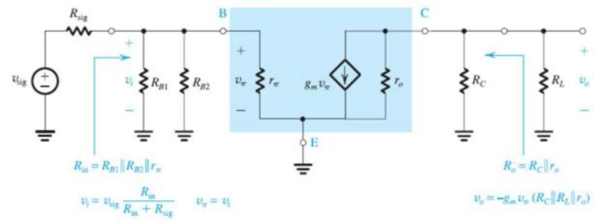

Figure 6. Equivalent Circuit and Analysis of Circuit Fig. 5

By refering to Fig 6. above,

$$R_{in} = R_{B1} \| R_{B2} \| r_\pi \quad (2)$$

Next, we will calculate R_{B1} (R_1) and R_{B2} (R_2) as follows. As a rule of thumb, we will design for V_B about $\frac{1}{3}V_{CC}$. For example, if we use $V_{CC} = 12\ V$, then we have

$$V_B = \frac{1}{3}V_{CC} = \frac{1}{3} \times 12\ V = 4\ V$$

Suppose that the design is for $I_E \approx 2\ mA$. We therefore select a voltage-divider current $I_{R_1R_2}$ of $0.1I_E = 0.1 \times 2\ mA = 0.2\ mA$. Thus, we have

$$(R_1 + R_2) = \frac{V_{CC}}{I_{R_1R_2}} = \frac{12\ V}{0.2\ mA} = 60\ k\Omega$$

$$\frac{R_2}{R_1 + R_2} = \frac{1}{3} \quad \left(because\ V_{R_2} = 3\ V\ and\ V_{R_1+R_2} = 9\ V\right)$$

$$\therefore$$

$$R_1 = 40\ k\Omega \ \text{ and } \ R_2 = 20\ k\Omega$$

Next, to calculate R_E, we use the expression

$$R_E = \frac{V_E}{I_E} = \frac{V_B - V_{BE}}{I_E} = \frac{4V - 0.7V}{2\ mA} = \frac{3.3\ V}{2\ mA} = 1.65\ k\Omega$$

The transistor used here is the $BF517$ which is a BJT silicon RF transistor (for amplifier and oscillator application in TV tuners), with its specifications shown in Table 1.

Table 1. Rating of Any Single BF517 Transistor

Parameter	Values	Unit
V_{BE}	0.7	Volt
I_C	25	mA
h_{FE} (β)	99.655	-
V_A	90.000	Volt

Now for any BJT transistor, we have a parameter called g_m, which is the transconductance of the transistor, given by

$$g_m = \frac{I_C}{V_T}$$

where $V_T = \frac{kT}{q}$ is the thermal voltage which has a value of approximately $25\ mV$ at room temperature $300\ K$. And another parameter called internal resistance of the transistor, given by

$$r_\pi = \frac{\beta}{g_m}$$

By using the parameter values from the Table 1 above, we obtain

$$g_m = \frac{I_C}{V_T} = \frac{2\ mA}{0.025\ V} = 80\frac{mA}{V}$$

and

$$r_\pi = \frac{\beta}{g_m} = \frac{99.655}{80\ mA/V} = 1.2456875\ k\Omega$$

We are now able to calculate the input resistance of the CE amplifier R_{in} by using (2) as follows

$$R_{in} = 40\ k\Omega \ \|\ 20\ k\Omega \ \|\ 1.2456875\ k\Omega \approx 1.139\ k\Omega$$

We now will determine the voltage gain A_v of the CE amplifier in Fig. 5 above. First, determine r_e as follows

$$r_e \cong \frac{1}{g_m} = \frac{V_T}{I_C} = \frac{26\ mV}{2\ mA} = 13\ \Omega$$

and then determine R_C as follows. This CE amplifier was designed to obtain $V_C = +8.2\ V$.

$$V_{CC} = V_C + I_C R_C$$

$$R_C = \frac{V_{CC} - V_C}{I_C} = \frac{12\ V - 8.2\ V}{2\ mA} = 1.9\ k\Omega$$

The voltage gain A_v with the bypass capacitor installed now can be obtained, which is

$$A_v = -\frac{R_C}{r_e} = -\frac{1.9\ k\Omega}{13\ \Omega} = -146.154$$

The negative sign of equation above reveals a 180° phase shift between V_o and V_i .

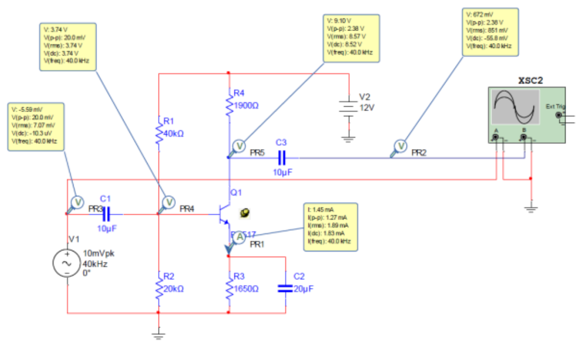

Figure 7. The Designed *CE* Voltage Divider Bias Circuit

When the single stage CE amplifier was simulated with the Multisim Interactive Simulation Active Analysis, the following Fig. 7 results were obtained. Note that $V_{in} = 10\ mV\ (peak\ to\ peak)$.

Table 2. Important Voltage and Current Values of Circuit Fig. 7.

Parameter	Calculated Values		Simulated Values	
$V_{in(p-p)}$	20	mV	20	mV
$V_{out(p-p)}$	3.040	Volt	2,380	Volt
$V_{B(dc)}$	4	Volt	3,74	Volt
$V_{C(dc)}$	8.2	Volt	8.52	Volt
$I_{E(dc)}$	2	mA	1.83	mA

It can be shown from the Table 2 that all the voltage and current values are in quite agreement with the calculated values.

6. RF and IF Amplifier

Let us have a look at a simple AM radio. The signal that is transmitted is a sinewave at the station's frequency in the AM band $(520\ kHz - 1720\ kHz)$, with its amplitude varied ("modulated") according to the audio waveform (see Figure 8) [10].

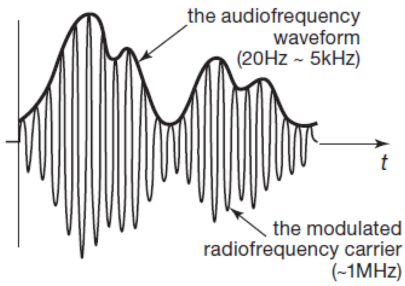

Figure 8. An AM Signal Consists of an RF Carrier Whose Amplitude is Varied by the Audio-Frequency Signal (Speech Or Music; Audible Frequencies up to $\sim 5kHz$). The Audio Waveform is DC Offset so that the Envelope Does not Cross Zero.

In other words, an audio waveform described by some function $f(t)$ (where $f(t)$ has a frequency much lower than f_c) would be transmitted as an RF signal $[A + f(t)]$ sin $2\pi f_c t$; here f_c is the station's "carrier" frequency, and the constant A is added to the audio waveform so that the coefficient $[A + f(t)]$ is never negative (i.e. the audio frequency waveform always has positive values).

At the receiver end (that's this circuit designed here) the task is to select this station (among many) and somehow extract the modulating *envelope*, which is the desired audio signal [10].

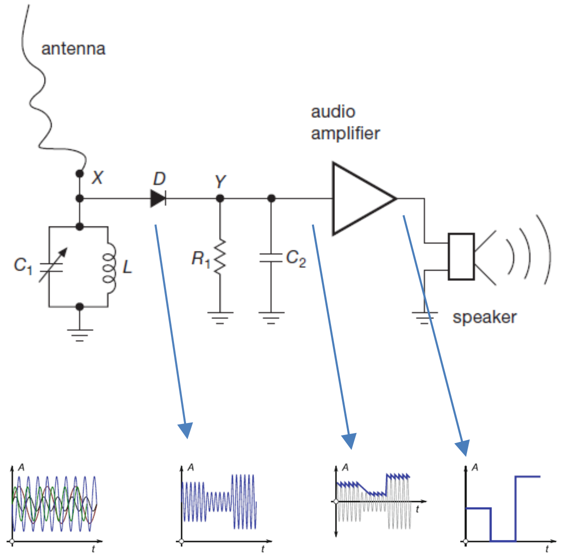

Figure 9. The Simplest AM Receiver. Variable Capacitor C_1 Tunes the Desired Station, Diode D Picks Off the Positive Envelope (smoothed by R_1C_2), and the Resulting Weak Audio Signal is Amplified to Drive the Loudspeaker, Loudly [10][12].

Figure 9 shows the simplest AM radio. After a weak radio frequency (RF) signal has arrived at the antenna, it is channeled to the input terminals of the RF amplifier through a passive matching network. The matching network enables maximum power transfer of the receiving signal by equalizing the antenna impedance with the RF amplifier input impedance. After that, it is job of the RF amplifier to increase the power of the received signal and prepare it for further processing [10].

The first three stages of a radio receiver, the antenna, the matching network, and the RF amplifier, are often referred to as the front-end of the RF radio receiver (see Fig. 10).

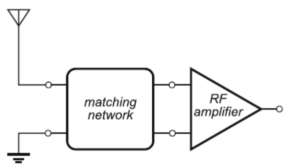

Figure 10. The First Three Main Stages of RF Radio Receiver

Thus, an RF amplifier is different from a baseband amplifier in that:

- The frequency range of operation of an RF amplifier must be "aligned" (i.e., tuned) with the centre frequency of the matching network, which, in turn, is tuned with the antenna.
- The bandwidth of the RF amplifier should be similar to the bandwidth of the incoming message, approximately 20 kHz in the case of music. That is,

the RF amplifier bandwidth should be not too wide, causing a decrease of SNR, or too narrow, introducing signal distortions (keep in mind Fourier).

Of the three single transistor amplifier types (i.e., CE, CB, and CC), the emitter follower is the only one that has voltage gain slightly less than unity, therefore we focus on the other two variants. Then, from the remaining two, we will choose the CE type.

6.1. Single-Stage CE RF Amplifier

As mentioned before, in principle a single-stage CE voltage amplifier is easily turned into a CE RF amplifier with two modifications: the collector's resistive load R_C is replaced by an $L_C C_C$ resonator; and an $L_B C_B$ resonator is connected between the input node and the ground. The result is as shown in Fig. 11.

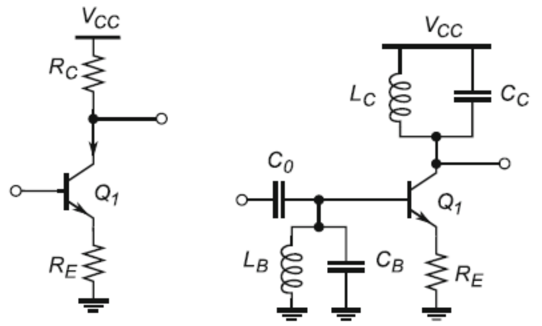

Figure 11. A CE Amplifier *(left)* and Its Equivalent CE RF Amplifier *(right)*.

Both resonators are tuned to the same resonant frequency ω_0. The input AC signal is then injected into the base through decoupling capacitor C_0, whose impedance is negligible at the resonator frequency ω_0 [12].

7. Selectivity and Bandwidth

The ability of a resonating circuit to select and amplify a weak voltage signal at one specific frequency ω_0 is its core quality used in RF circuits, it is referred to as "selectivity". In the ideal case of $Q \to \infty$, the resonating circuit would pick one and only one frequency, ω_0, while all other tones would be completely suppressed. However, in realistic circuits there is always some finite resistance causing the thermal loss, which is measured by the circuit's finite Q factor. A plot of selectivity curves as a function of Q factor is shown in Fig. 12. The plot indicates that, for good selectivity, we need high Q factor resonating circuits [12].

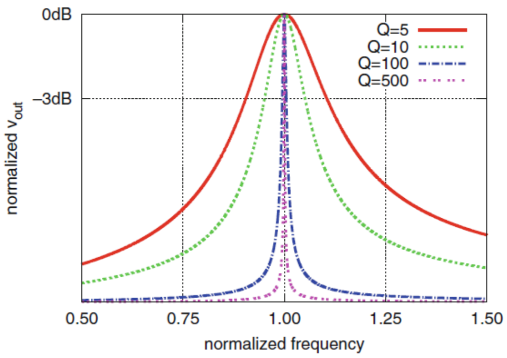

Figure 12. Normalized output voltage across the inductor at normalized resonant frequency $\omega_0 = 1$ for various Q factors

While Fig. 13 shows the bandwidth definition plot, where f_1 corresponds to ω_L and f_2 corresponds to ω_U. The two frequencies are at $-3\ dB$ points relative to the maximum amplitude of the resonator (which is at ω_0).

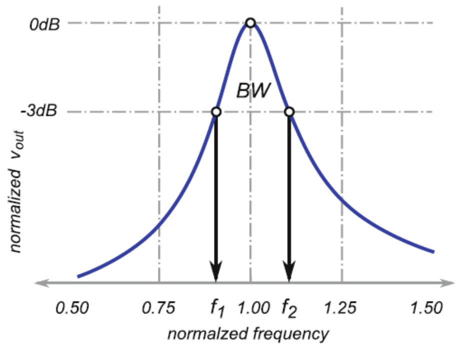

Figure 13. Bandwidth Definition Plot Where f_1 Corresponds to ω_L, and f_2 Corresponds to ω_U

We now come to the process of calculating the selectivity and the bandwidth of the resonant circuit which will be employed in this RF amplifier. A parallel resonant circuit which composed of the following tank circuit elements will be designed: $C = 47\ pF$, $L = 1\ mH$ with internal wire resistance of $R_L = 125.7\ \Omega$. The resonant circuit will have a resonant frequency $f_0 \cong 734.127\ kHz$

First, we calculate the quality factor of the coil $Q_L = \frac{X_L}{R_L} = \frac{2\pi f_0 L}{R_L} = \frac{2\pi(734.127\ kHz)(1\ mH)}{125.7\ \Omega} = 36.696$. Since $Q_L \geq 10$, therefore $Z_{max} \cong Q_L^2 R_L = (36.696)^2(125.7\ \Omega) \cong 169.265\ k\Omega$.

The bandwidth BW can be calculated as $BW = \frac{f_0}{Q_L} = \frac{R_L}{2\pi L} = \frac{125.7\ \Omega}{2\pi(1\ mH)} = 20005\ Hz \cong 20\ kHz$.

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The two frequency points, the "lower" and "upper" frequencies are determined as follows. The "lower" frequency is [13].

$$f_1 = \frac{1}{4\pi C}\left[\frac{1}{R} - \sqrt{\frac{1}{R^2} + \frac{4C}{L}}\right]$$

$$= \frac{1}{4\pi(47\ pF)}\left[\frac{1}{39\ k\Omega} - \sqrt{\frac{1}{(39\ k\Omega)^2} + \frac{4(47\ pF)}{1\ mH}}\right]$$

$$= 1.693 \times 10^9[2.564\ \times 10^{-5} - 4.343 \times 10^{-4}]$$

$$= 1.693 \times 10^9[-4.0866 \times 10^{-4}] = 691.861\ kHz$$

(ignoring the negative sign). And the "upper" frequency is

$$f_2 = \frac{1}{4\pi C}\left[\frac{1}{R} + \sqrt{\frac{1}{R^2} + \frac{4C}{L}}\right]$$

$$= \frac{1}{4\pi(47\ pF)}\left[\frac{1}{39\ k\Omega} + \sqrt{\frac{1}{(39\ k\Omega)^2} + \frac{4(47\ pF)}{1\ mH}}\right]$$

$$= 1.693 \times 10^9[2.564\ \times 10^{-5} + 4.343 \times 10^{-4}]$$

$$= 1.693 \times 10^9[4.5994 \times 10^{-4}] = 778.678\ kHz$$

Note that $f_2 - f_1 = 778.678\ kHz - 691.861\ kHz = 86.817\ kHz$ [10].

For the signal amplification, we will use the single stage CE amplifier that has been built under the section Single Stage Common-Emitter Voltage Amplifier above.

8. The Designed CE RF Circuit

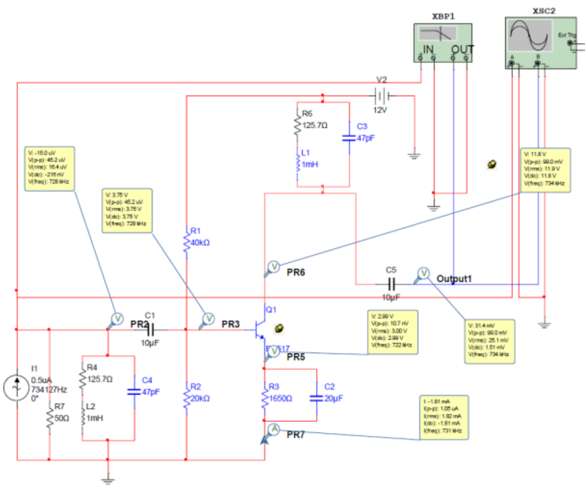

Figure 14. The Design Result of the $CE\ RF$ Amplifier

The $CE\ RF$ circuit that results from the design process above can be shown in Fig. 14. It is a CE with tuned circuits at both the input and the output. The input resonator and the output resonator both are tuned to the same resonant frequency of magnitude $\omega_0 = 2\pi f_0 = 2\pi(734127\ Hz) = 4612655.98\ rad/s$. Also note that because the input circuit is a parallel resonant circuit, an input current source (rather than voltage source) signal is utilized.

At the output side, the collector's resistive load R_C has been replaced by an $L_C C_C$ resonator. And at the input side, an $L_B C_B$ resonator is connected between the input node and the ground.

The bias details are also shown, from which biasing is quite similar to the classical arrangement employed in low-frequency, discrete-circuit design. The values of the two base resistances R_1 and R_2 determine the DC point of the sinusoidal signal. When the circuit was simulated with the Multisim Active Analysis AC Sweep, the following results were obtained

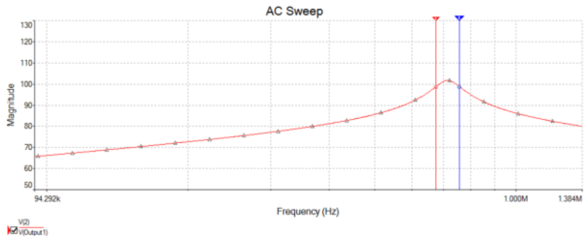

Figure 15. Multisim AC Sweep Active Analysis of the $CE\ RF$ Amplifier. Shown is the Output Voltage V_{out}

Figure 15 is the magnitude plots for the output voltage. It can be shown that the maximum value is $101.7115\ dB$. By moving the blue cursor until we reach those maximum value, we can find the resonant frequency. This is achieved at $714.0183\ kHz$. Those two cursors can also be used to define the high cutoff frequency for the bandwidth by first calculating the $-3\ dB$ level of the output voltage. The result is $101.7115\ dB - 3\ dB = 98.7115\ dB$. The closest we can come to this level with the cursor is $98.7333\ dB$ which defines a frequency of $757.3257\ kHz$ and $675.0777\ kHz$. The resulting bandwidth is therefore $757.3257\ kHz - 675.0777\ kHz = 82.25\ kHz$ which is in quiet agreement with the calculated result of $86.817\ kHz$.

9. Miller Capacitance (Miller Effect)

In this section we will discuss the infamous *Miller effect*, and the use of cascode configuration to overcome it.

The single-stage common-emitter voltage amplifier satisfies all three conditions required for the Miller effect. It is an inverting amplifier, it has gain larger than one, and it has a capacitive component that creates an AC path between the input and output terminals (in Fig. 16, it is shown as the capacitor C_{CB} connected between the transistor's collector and base)

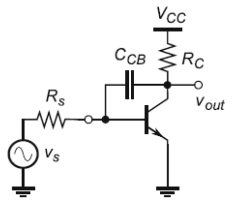

Figure 16. A single CE Voltage Amplifier with Miller Capacitance Caused by C_{CB}

This feedback impedance C_{CB} is a matter. The amplifier has some overall voltage gain A_V, so a small voltage wiggle at the input results in a wiggle A_V times larger (and inverted) at the collector. The feedback capacitance behaves like a capacitor of value $C_{CB}(1 + A_V)$ from input to ground. This effective increase of C_{CB} is known as the Miller effect. It often dominates the roll-off characteristics of amplifiers, because a typical feedback capacitance of $4\,pF$ can look like several hundred picofarads to ground [12].

There are several methods available for beating this Miller effect: differential amplifier with inverting input grounded, grounded base amplifier, and cascode connection. Of those three, the cascode connection will be employed in this research.

The famous cascode configuration (see Fig. 17) elegantly defeats the Miller effect. The purpose of the cascode amplifier is to reduce the Miller effect [16]. It provides high voltage gain over a wider range of frequencies that can be achieved by a common-emitter stage [15].

The cascode is a very useful two-transistor stage that provides the performance of a common-emitter stage with a much smaller Miller effect and much larger output resistance. The stage was first introduced to get better high-frequency performance, and the higher output resistance was viewed as a bonus [7].

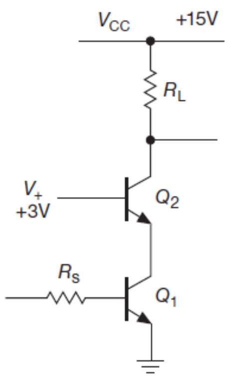

Figure 17. The Cascode Connection Circuit Configuration that Will Avoid the Miller Effect.

10. DC Analysis of a Cascode Amplifier

The dc analysis of a cascode amplifier of Fig. 18 can be explained as follows.

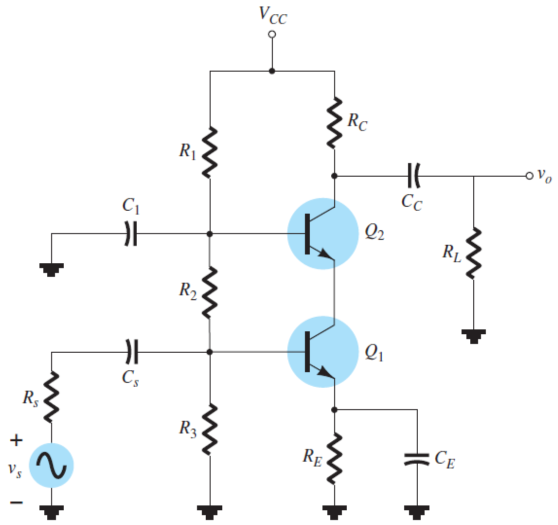

Figure 18. A Cascode Amplifier

The dc analysis is initiated by assuming the current through the bias resistors R_1, R_2 and R_3 of Fig. 19 is much larger than the base current of each transistor [14]. That is,

$$I_{R_1} \cong I_{R_2} \cong I_{R_3} \gg I_{B_1} \; or \; I_{B_2}$$

The result is that the voltage at the base of the transistor Q_1 is simply determined by an application of the voltage-divider rule:

$$V_{B_1} = \frac{R_3}{R_1 + R_2 + R_3} V_{CC}$$

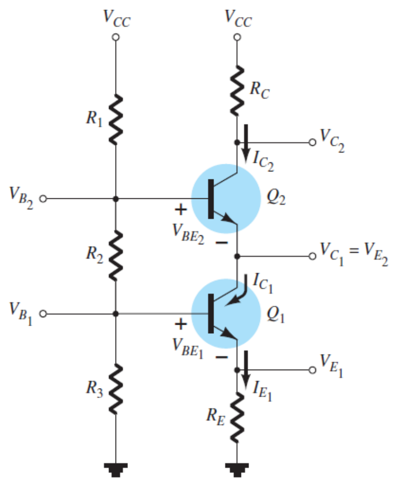

Figure 19. DC Equivalent of Fig. 18

The voltage at the base of the transistor Q_2 is found in the same manner:

$$V_{B_2} = \frac{(R_2 + R_3)}{R_1 + R_2 + R_3} V_{CC}$$

The emitter voltages are then determined by

$$V_{E_1} = V_{B_1} - V_{BE_1}$$

and

$$V_{E_2} = V_{B_2} - V_{BE_2}$$

with the emitter and collector currents determined by:

$$I_{C_2} \cong I_{E_2} \cong I_{C_1} \cong I_{E_1} = \frac{V_{B_1} - V_{BE_1}}{R_{E_1} + R_{E_2}}$$

The collector voltage V_{C_1}:

$$V_{C_1} = V_{B_2} - V_{BE_2}$$

and the collector voltage V_{C_2}:

$$V_{C_2} = V_{CC} - I_{C_2} R_C$$

The current through the biasing resistors is

$$I_{R_1} \cong I_{R_2} \cong I_{R_3} = \frac{V_{CC}}{R_1 + R_2 + R_3}$$

and each base current is determined by

$$I_{B_1} = \frac{I_{C_1}}{\beta_1}$$

with

$$I_{B_2} = \frac{I_{C_2}}{\beta_2}$$

11. Removing Miller Effect with Cascode Amplifier

We can improve the frequency-dependent behaviour of a CE amplifier in RF applications by looking at the three conditions for the Miller effect one by one. We cannot do anything about its inherent inverting signal nature and we do need to keep the high voltage gain. For all practical purposes, we cannot remove the Miller effect by modifying those two conditions. The only option left is to find out if we can do anything about the bridging I/O capacitance.

As a matter of fact, that not having the I/O bridging capacitance protects a CB amplifier configuration from the Miller effect. That gives us an idea of how to modify a simple CE stage and improve its bandwidth by turning it into a cascode amplifier. An additional, and not so obvious, feature of a cascode amplifier architecture is that the insertion of a CB stage between the CE output node (the collector of Q_1) and the load resistor R_C effectively removes the capacitive connection between the input and the output nodes of the cascode amplifier, Fig. 20 [12].

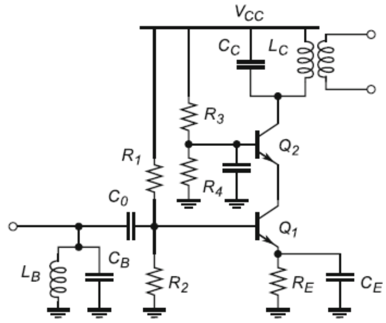

Figure 20. A Cascode *BJT RF* Amplifier

The collector–base capacitance C_{CB} of Q_1 connects the input terminal of the cascode amplifier with one of its internal nodes, while at the same time the cascode amplifier output terminal is taken from the CB amplifier output node (the collector of Q_2), which is safely disconnected (i.e., "buffered") from the input terminal. This property makes the cascode amplifier immune to the Miller effect.

12. The Cascode CE-CB Amplifier

When the CE circuit of Fig. 7 was converted into a cascode amplifier, the circuit of Fig. 21 results

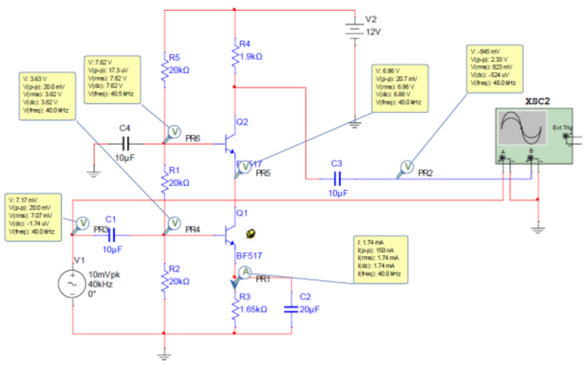

Figure 21. The Cascode $CE - CB$ Amplifier

The dc analysis for the circuit of Fig. 21 produces the values as shown in Table 3.

Table 3. Important Voltage and Current Values of Circuit Fig. 21.

Voltage	Values	
V_{B_1}	4	V
V_{B_2}	8	V
$I_{C_2} \cong I_{E_2} \cong I_{C_1} \cong I_{E_1}$	2	mA
r_e	13	Ω

The loading on the transistor Q_1 is the input impedance of the Q_2 transistor in the CB configuration as shown by r_e in Fig 22.

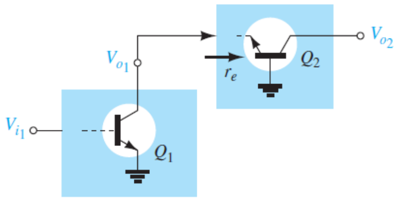

Figure 22. Defining the Load of Q_1 .

The result is the replacement of R_C in the basic no-load equation for the gain of the CE configuration, with the input impedance of a CB configuration as follows:

$$A_{v_1} = -\frac{R_C}{r_e} = -\frac{r_e}{r_e} = -1$$

with the voltage gain for the second stage (common base) of

$$A_{v_2} = \frac{R_C}{r_e} = \frac{1.9\ k\Omega}{13\ \Omega} = 146.154$$

The overall no-load gain is

$$A_{v_T} = A_{v_1} A_{v_2} = (-1)(146.154) = -146.154$$

As expected, the CE stage provides a higher input impedance than can be expected from the CB stage. With a voltage gain of about 1 for the first stage, the Miller-effect input capacitance is kept quite low to support a good high-frequency response. A large voltage gain of 146.154 was provided by the CB stage to give the overall design a good input impedance level with desirable gain levels. When the circuit if Fig. 21 was simulated with the Multisim AC Sweep Active Analysis, the results was as follows

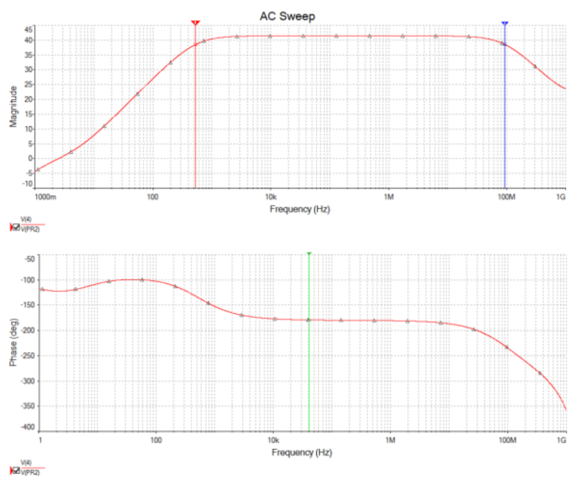

Figure 23. Magnitude and Phase Plot of the Cascode $CE - CB$ Amplifier of Fig. 25

The upper graph of Fig. 23 shows the frequency response of this cascode $CE - CB$ amplifier system. We have been assuming that our amplifier are operating in the middle-frequency band. The amplifier is designed so that its midband coincides with the frequency spectrum of the signals it is required to amplify.

The bandwidth (or passband) is determined by f_H and f_L, that is,

$$bandwidth\ (BW) = f_H - f_L =$$

Where f_L and f_H define the lower end and the upper end of the midband. They are defined as the frequency at which the gain drops by 3 dB below its value in midband.

The lower graph reveals a 180° phase shift between output voltage $V_o\ (phase = -180°)$ and input voltage $V_i\ (phase = 0°)$. This is because the overall no-load gain is negative.

13. The CE – CB Cascode RF Amplifier

Next, the design results for the CE – CB cascode RF amplifier can be shown in the Fig. 24.

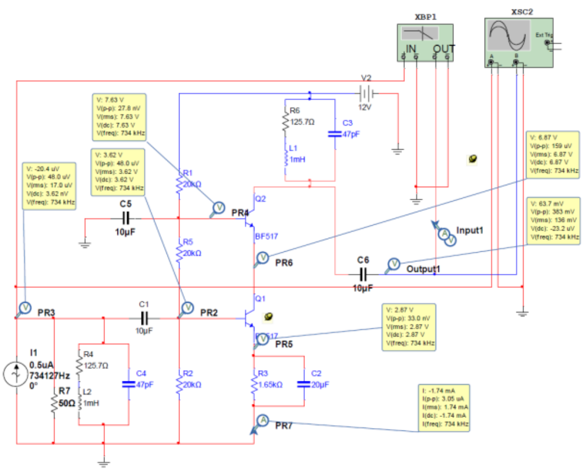

Figure 24. The Cascode $CE - CB$ RF Amplifier

Table 4. Important Voltage and Current Values of Circuit Fig. 21.

Voltage	Values	
V_{B_1}	4	$Volt$
V_{B_2}	8	$Volt$
$I_{C_2} \cong I_{E_2} \cong I_{C_1} \cong I_{E_1}$	2	mA
r_e	13	Ω
V_{E_1}	3.3	$Volt$
V_{E_2}	7.3	$Volt$
V_{C_1}	7.3	$Volt$

The circuit of Fig. 24 is exactly the same in appearance as Fig. 21 except that there are now two "tuned circuit". The first "tuned circuit" replaces the resistive load R_C, and the second one is connected between the input node and the ground.

The DC analysis calculation for the circuit of Fig. 24 has been done in the previous section, the results of which are repeated again in Table 4.

In order to be able to calculate the overall no-load gain, we need to calculate the impedance of the $L_C C_C$ resonator. The reactance of the inductor must be calculated first:

$$X_L = 2\pi f L = 2\pi \times 734.127\ kHz \times 1mH$$
$$= 4612.65598\ \Omega$$

Then, the series impedance of $R_6 = 125.7\ \Omega$ and $L = 1\ mH$ is calculated as follows.

$$Z_{R-L} = Z_R + Z_L = 125.7\ \Omega + j\ 4612.65598\ \Omega$$
$$Z_{R-L} = 4614.368\ \Omega \angle 88.439°$$

Next, the parallel impedance between $Z_{R-L} = 4614.368\ \Omega \angle 88.439°$ and the impedance of the $47\ pF$ capacitor can be calculated. First, the reactance of the capacitor must be calculated as follows:

$$Z_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 734.127\ kHz \times 47\ pF}$$
$$= 4612.656\ \Omega \angle -90°$$
$$= -j\ 4612.656\ \Omega$$

Then, the total (parallel) impedance between Z_C and Z_{R-L} is

$$Z_T = \frac{Z_C\, Z_{R-L}}{Z_C + Z_{R-L}}$$

$$= \frac{(4612.656\ \Omega \angle -90°)(4614.368\ \Omega \angle 88.439°)}{-j\ 4612.656\ \Omega + 125.7\ \Omega + j\ 4612.65598\ \Omega}$$

$$\cong \frac{21284492.2414\ \Omega \angle -1.561°}{125.7\ \Omega}$$
$$\cong 169327.7\ \Omega \angle -1.561°$$

and now the voltage gain for the second stage (common base) of

$$A_{v_2} = \frac{Z_T}{r_e} = \frac{169327.70\ \Omega}{13\ \Omega} = 13025.20$$

and the overall no-load gain can be calculated as follows:

$$A_{v_T} = A_{v_1} A_{v_2} = (-1)(13025.20) = -13025.20$$

The overall no-load gain and magnitude of various voltage and current shown in Fig. 24 above were tabulated in Table 5 below.

Table 5. Various Voltage and Current Values of Fig. 24

Voltage / Current	Calculated	Simulated
V_{B_1}	$4\ V$	$3.62\ V$
V_{B_2}	$8\ V$	$7.63\ V$
V_{E_1}	$3.3\ V$	$2.87\ V$
V_{E_2}	$7.3\ V$	$6.87\ V$
$I_{C_2} \cong I_{C_1}$	$2\ mA$	$1.74\ mA$
V_{C_1}	$7.3\ V$	$6.87\ V$
A_{v_T}	-13025.20	-8083.33

When the circuit of Fig. 24 was simulated with Multisim AC Sweep Active Analysis, the results was shown as in Fig. 25.

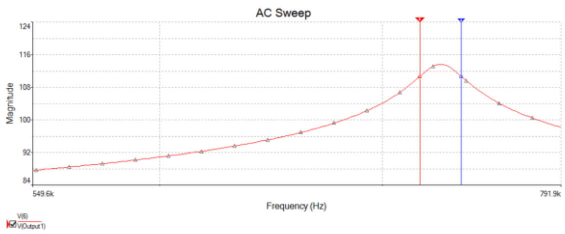

Figure 25. Frequency Characteristic for the Tuned Circuit of Circuit Fig. 24

It can be seen from the magnitude plot graph of Fig. 25, that the peak voltage was achieved at frequency of $729.30\ kHz$. By using two cursors, the "lower" frequency $f_1 = 718.246\ kHz$ (the left cursor) and the "upper" frequency $f_2 = 739.012\ kHz$ (the right cursor). Thus, giving the tuned amplifier a bandwidth of $739.012\ kHz - 718.246\ kHz = 20.766\ kHz$. This simulation bandwidth is in quite agreement with the calculation bandwidth of $\cong 20\ kHz$.

14. Conclusion

From this research, it can be shown that an BJT cascode RF amplifier has been successfully designed. The tuned amplifier has been able to selects a particular range of frequencies (which is $\cong 734\ kHz$ with a bandwith of $\cong 20\ kHz$) and rejects the other undesired frequencies. The cascode configuration has made an improvement in terms of its bandwidth. By employing this cascode configuration, the RF amplifier has a midband frequencies range between $\cong 500\ Hz$ up to $\cong 100\ MHz$.

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