Biasing Bipolar Junction Transistors

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W5LUA

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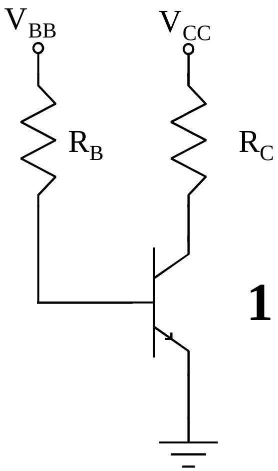
Various BJT Biasing Networks



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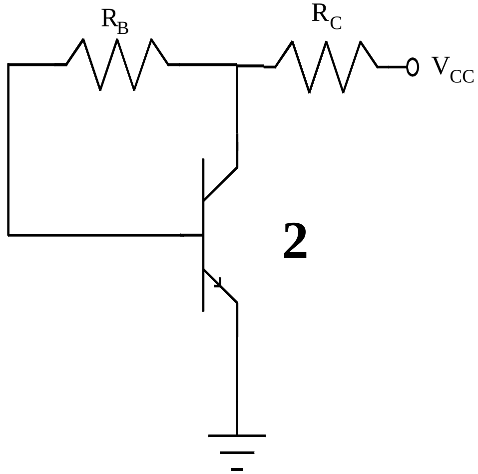

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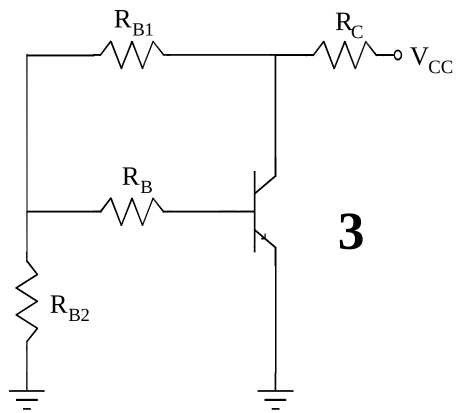

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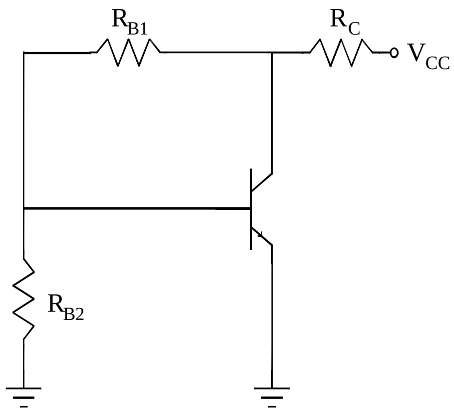

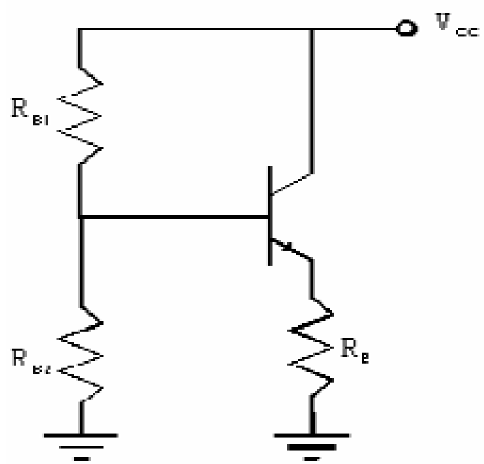

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AT-41486

Electrical Specifications, $T_A = 25°C$

Symbol	Parameters and Test Conditions		Units	Min.	Typ.	Max.
$\|S_{21E}\|^2$	Insertion Power Gain; $V_{CE} = 8$ V, $I_C = 25$ mA	f = 1.0 GHz f = 2.0 GHz	dB		17.5 11.5	
$P_{1\,dB}$	Power Output @ 1 dB Gain Compression $V_{CE} = 8$ V, $I_C = 25$ mA	f = 2.0 GHz	dBm		18.0	
$G_{1\,dB}$	1 dB Compressed Gain; $V_{CE} = 8$ V, $I_C = 25$ mA	f = 2.0 GHz	dB		13.5	
NF_O	Optimum Noise Figure: $V_{CE} = 8$ V, $I_C = 10$ mA	f = 1.0 GHz f = 2.0 GHz f = 4.0 GHz	dB		1.4 1.7 3.0	1.8
G_A	Gain @ NF_O; $V_{CE} = 8$ V, $I_C = 10$ mA	f = 1.0 GHz f = 2.0 GHz f = 4.0 GHz	dB	17.0	18.0 13.0 9.0	
f_T	Gain Bandwidth Product: $V_{CE} = 8$ V, $I_C = 25$ mA		GHz		8.0	
h_{FE}	Forward Current Transfer Ratio; $V_{CE} = 8$ V, $I_C = 10$ mA		—	30	150	270
I_{CBO}	Collector Cutoff Current; $V_{CB} = 8$ V		µA			0.2
I_{EBO}	Emitter Cutoff Current; $V_{EB} = 1$ V		µA			1.0
C_{CB}	Collector Base Capacitance[1]: $V_{CB} = 8$ V, f = 1 MHz		pF		0.25	

Note:
1. For this test, the emitter is grounded.

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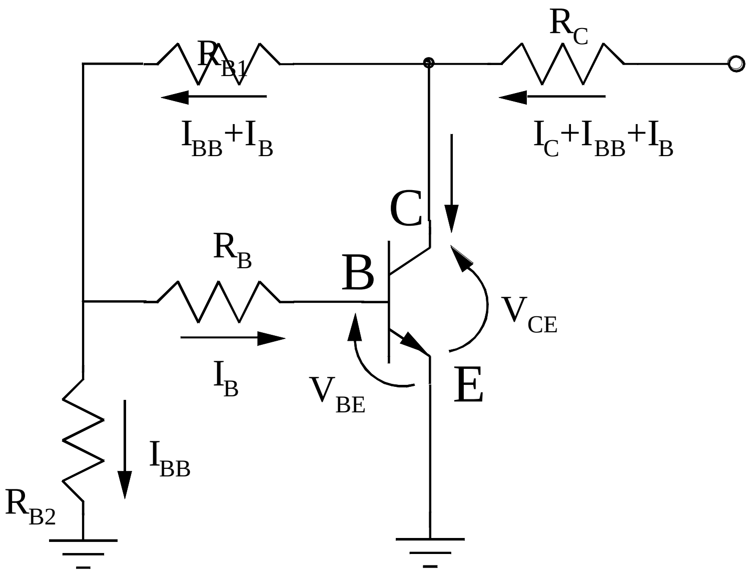
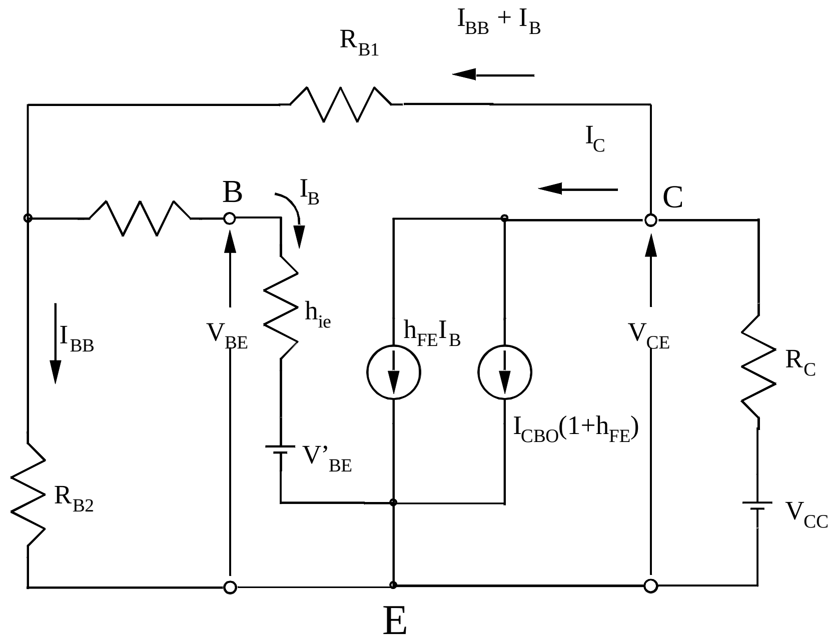
Bipolar Transistor Bias Network Analysis





A. Bias circuit showing only the DC components.

B. The equivalent circuit of figure A used in DC stability analysis.

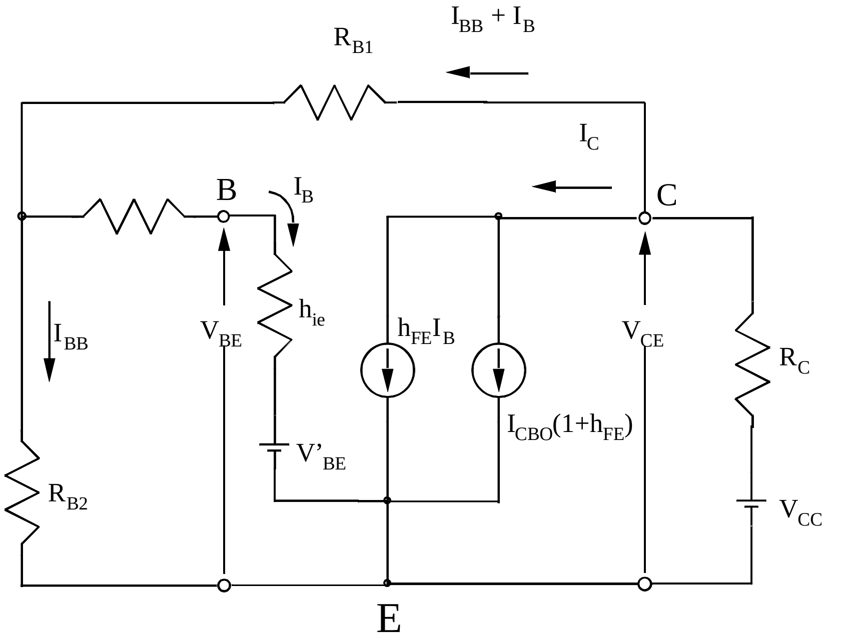
$I_C = h_{FE}\, I_B + I_{CBO}\,(1+h_{FE})$

- where h_{FE} is the DC current gain of the transistor and I_{CBO} is the current flowing through a reverse biased PN junction.

$V_{BE} = V'_{BE} + I_B\, h_{ie}$

- where V'_{BE} is internal to the transistor and h_{ie} is the equivalent Hybrid Π input resistance of the transistor and is equal
- to $h_{FE} / (\lambda Ic)$ where λ=40 @ +25 degrees C. h_{ie} is generally much smaller than Rb

Temperature Sensitive Parameters



The equivalent circuit of the voltage feedback and constant base current source bias network used in DC stability analysis.

V'_{BE}, h_{FE}, I_{CBO}

V'_{BE} has a typical negative temperature coefficient of -2mV/°C.

h_{FE} typically increases with temperature at the rate of 0.5%/°C.

I_{CBO} typically doubles for every 10°C temperature rise.

Non-Stabilized Bias Network #1

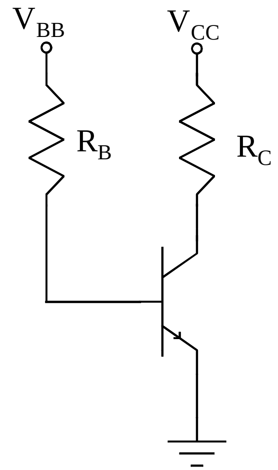
$V_{CC} = V_{BB} = 2.7V$, $V_{CE} = 2V$, $I_C = 5$ mA, $h_{FE} = 80$, 50 min, 150 max

$V_{BE} = 0.78$ V, $I_{CBO} = 1x10^{-7}$ A @ +25 deg C

$$R_B := \frac{V_{CC} - V_{BE}}{I_B} \qquad R_C := \frac{V_{CC} - V_{CE}}{I_C}$$

$R_B = 30770$ ohms

$R_C = 140$ ohms

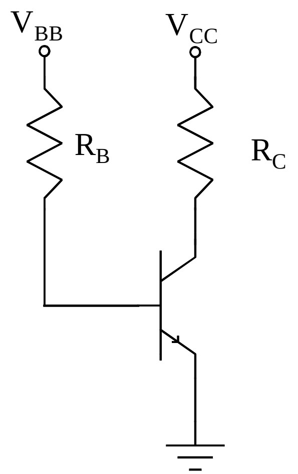


Non-Stabilized Bias Network #1

$V_{CC} = V_{BB} = 2.7V$, $V_{CE} = 2V$, $I_C = 5$ mA, $h_{FE} = 80$, 50 min, 150 max

$V_{BE} = 0.78$ V, $I_{CBO} = 1x10^{-7}$ A @ +25 deg C

$$I_C := \frac{h_{FE} \cdot (V_{CC} - V'_{BE})}{(h_{ie} + R_B)} + I_{CBO} \cdot (1 + h_{FE})$$



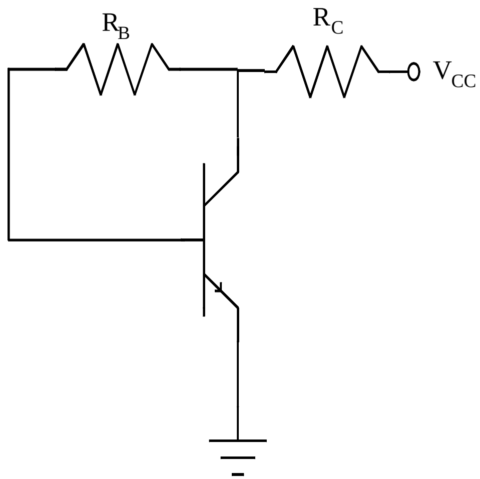
Based on h_{FE} alone
I_C max = 9.27 mA
I_C min = 3.14 mA

Voltage Feedback Bias Network #2

V_{CC} = 2.7V, V_{CE} = 2V, I_C = 5 mA, h_{FE} = 80, 50 min, 150 max

V_{BE} = 0.78 V, I_{CBO} = $1x10^{-7}$ A @ +25 deg C

$$R_B := \frac{V_{CE} - V_{BE}}{I_B} \qquad R_C := \frac{V_{CC} - V_{CE}}{I_C + I_B}$$



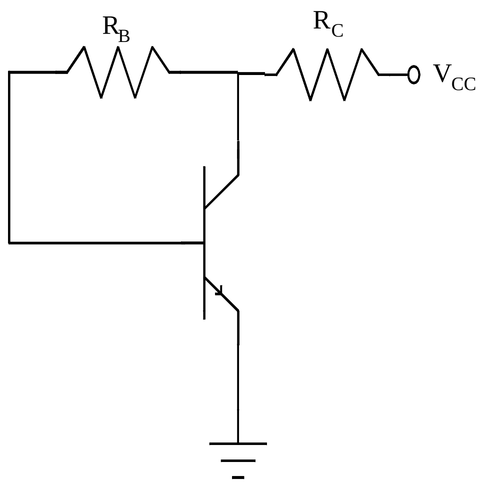
R_B = 19552 ohms R_C = 138 ohms

Voltage Feedback Bias Network #2

V_{CC} = 2.7V, V_{CE} = 2V, I_C = 5 mA, h_{FE} = 80, 50 min, 150 max

V_{BE} = 0.78 V, I_{CBO} = 1x10^{-7} A @ +25 deg C

$$I_C := \frac{h_{FE}\cdot\left(V_{CC} - V'_{BE}\right) + I_{CBO}\cdot\left(1 + h_{FE}\right)\cdot\left(h_{ie} + R_B + R_C\right)}{h_{ie} + R_B + R_C\cdot\left(1 + h_{FE}\right)}$$

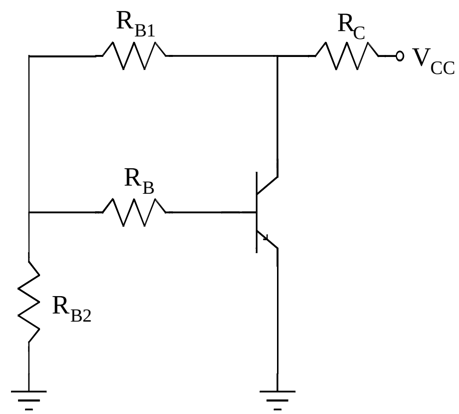


Based on h_{FE} alone
I_C max = 7.09 mA
I_C min = 3.63 mA

Voltage Feedback and Constant Base Current Source Bias Network #3

V_{CC} = 2.7V, V_{CE} = 2V, I_C = 5 mA, h_{FE} = 80 typ, 50 min, 150 max

V_{BE} = 0.78 V, I_{CBO} = $1x10^{-7}$ A @ +25 deg C



Choose V_{RB2}, in which $V_{CE} > V_{RB2} > V_{BE}$. Suggest a V_{RB2} of 1.5V

Suggest a voltage divider current of .5mA.

$$R_C := \frac{V_{CC} - V_{CE}}{I_C + I_{B2} + I_B} \qquad R_B := \frac{V_{RB2} - V_{BE}}{I_B}$$

$$R_{B1} := \frac{V_{CE} - V_{RB2}}{I_{B2} + I_B} \qquad R_{B2} := \frac{V_{RB2}}{I_{B2}}$$

R_C= 126 ohms
R_B = 11,539 ohms
R_{B1} = 889 ohms
R_{B2} = 3000 ohms

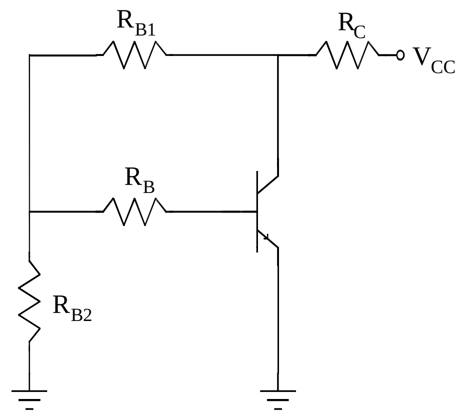
Voltage Feedback and Constant Base Current Source Bias Network #3

V_{CC} = 2.7V, V_{CE} = 2V, I_C = 5 mA, h_{FE} = 80 typ, 50 min, 150 max

V_{BE} = 0.78 V, I_{CBO} = 1x10^{-7} A @ +25 deg C

$$I_C := \left[\frac{-V'_{BE}\cdot\left(R_{B1}+R_{B2}+R_C\right)-R_{B2}\cdot\left[R_C\cdot I_{CBO}\cdot\left(1+h_{FE}\right)-V_{CC}\right]}{\left(R_B+h_{ie}\right)\cdot\left(R_{B1}+R_{B2}+R_C\right)+R_{B2}\cdot\left(h_{FE}\cdot R_C+R_C+R_{B1}\right)}\right]\cdot h_{FE}+I_{CBO}\cdot\left(1+h_{FE}\right)$$

Based on h_{FE} alone
I_C max = 6.98 mA
I_C min = 3.66 mA



Voltage Feedback Bias Network #4

V_{CC} = 2.7V, V_{CE} = 2V, I_C = 5 mA, h_{FE} = 80 typ, 50 min, 150 max

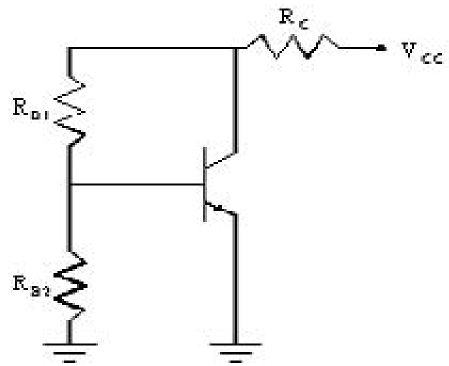
V_{BE} = 0.78 V, I_{CBO} = 1×10^{-7} A @ +25 deg C

Choose I_{B2}, suggest a voltage divider current of .5mA, to calculate R_{B2}.

$$R_{B2} := \frac{V_{BE}}{I_{B2}}$$

$$R_{B1} := \frac{V_{CE} - (I_{B2} \cdot R_{B2})}{I_B + I_{B2}}$$

$$R_C := \frac{V_{CC} - V_{CE}}{I_C + I_B + I_{B2}}$$



R_C= 126 ohms
R_{B1} = 2169 ohms
R_{B2} = 1560 ohms

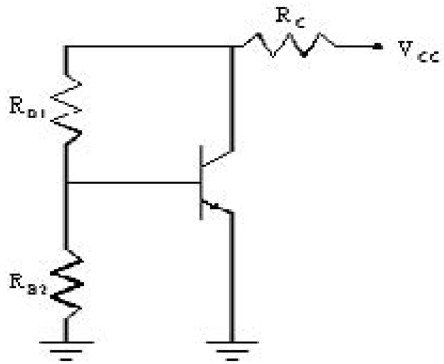
Voltage Feedback Bias Network #4

V_{CC} = 2.7V, V_{CE} = 2V, I_C = 5 mA, h_{FE} = 80 typ, 50 min, 150 max

V_{BE} = 0.78 V, I_{CBO} = 1x10^{-7} A @ +25 deg C

$$I_C := \frac{-\left[\frac{-R_C}{h_{FE}}\cdot I_{CBO} - R_C\cdot I_{CBO} + \frac{R_C}{R_{B2}}\cdot V'_{BE} - \frac{R_C}{\left(R_{B2}\cdot h_{FE}\right)}\cdot h_{ie}\cdot I_{CBO} - \frac{R_C}{R_{B2}}\cdot h_{ie}\cdot I_{CBO} - \frac{R_{B1}}{h_{FE}}\cdot I_{CBO} - R_{B1}\cdot I_{CBO} + \frac{R_{B1}}{R_{B2}}\cdot V'_{BE} - \frac{R_{B1}}{\left(R_{B2}\cdot h_{FE}\right)}\cdot h_{ie}\cdot I_{CBO} - \frac{R_{B1}}{R_{B2}}\cdot h_{ie}\cdot I_{CBO} + V'_{BE} - \frac{1}{h_{FE}}\cdot h_{ie}\cdot I_{CBO} - h_{ie}\cdot I_{CBO} - V_{CC}\right]}{\left[R_C + \frac{R_C}{h_{FE}} + \frac{R_C}{\left(R_{B2}\cdot h_{FE}\right)}\cdot h_{ie} + \frac{R_{B1}}{h_{FE}} + \frac{R_{B1}}{\left(R_{B2}\cdot h_{FE}\right)}\cdot h_{ie} + \frac{1}{h_{FE}}\cdot h_{ie}\right]}$$

Based on h_{FE} alone
I_C max = 5.44 mA
I_C min = 4.53 mA



Emitter Feedback Bias Network #5

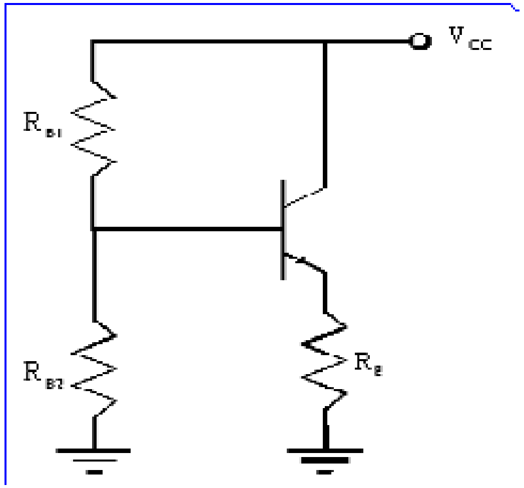
V_{CC} = 2.7V, V_{CE} = 2V, I_C = 5 mA, h_{FE} = 80 typ, 50 min, 150 max

V_{BE} = 0.78 V, I_{CBO} = 1x10^{-7} A @ +25 deg C

$$R_E := \frac{V_{CC} - V_{CE}}{\left[\frac{I_C - I_{CBO}\cdot(1 + h_{FE})}{h_{FE}}\right] + I_C} \qquad R_1 := \frac{V_{CC} - I_{B2}\cdot R_2}{I_{B2} + I_B}$$

Pick Ib2 of 10% of Ic which is equal to .0005

$$R_2 := \frac{V_{RB2}}{I_{B2}} \qquad V_{RB2} := V_{BE} + (I_B + I_C)\cdot R_E$$



R_E = 138 ohms
R_{B1} = 2169 ohms
R_{B2} = 2960 ohms

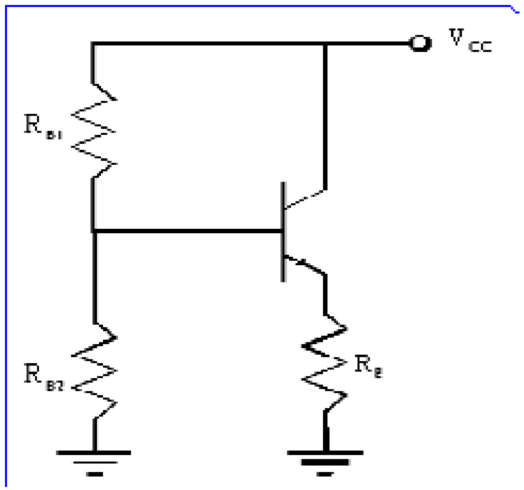
Emitter Feedback Bias Network #5

V_{CC} = 2.7V, V_{CE} = 2V, I_C = 5 mA, h_{FE} = 80 typ, 50 min, 150 max

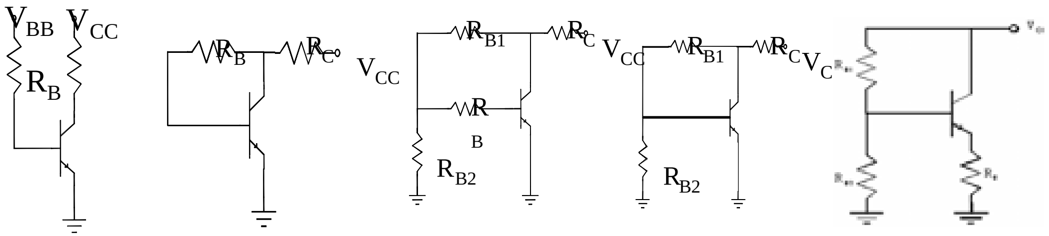
V_{BE} = 0.78 V, I_{CBO} = 1x10^{-7} A @ +25 deg C

$$I_C := \frac{-\left[V'_{BE} - \frac{1}{h_{FE}} \cdot h_{ie} \cdot I_{CBO} - h_{ie} \cdot I_{CBO} - \frac{R_E}{h_{FE}} \cdot I_{CBO} - R_E \cdot I_{CBO} + \frac{R_1}{R_2} \cdot V'_{BE} - \frac{R_1}{(R_2 \cdot h_{FE})} \cdot h_{ie} \cdot I_{CBO} - \frac{R_1}{R_2} \cdot h_{ie} \cdot I_{CBO} - \frac{R_1}{R_2} \cdot \frac{R_E}{h_{FE}} \cdot I_{CBO} - \frac{R_1}{R_2} \cdot R_E \cdot I_{CBO} - \frac{R_1}{h_{FE}} \cdot I_{CBO} - R_1 \cdot I_{CBO} - V_{CC}\right]}{\left[\frac{1}{h_{FE}} \cdot h_{ie} + \frac{R_E}{h_{FE}} + R_E + \frac{R_1}{(R_2 \cdot h_{FE})} \cdot h_{ie} + \frac{R_1}{R_2} \cdot \frac{R_E}{h_{FE}} + \frac{R_1}{R_2} \cdot R_E + \frac{R_1}{h_{FE}}\right]}$$

Based on h_{FE} alone
I_C max = 5.27 mA
I_C min = 4.70 mA



Summary of I_C Variation vs h_{FE} For All Bias Circuits



Bias Circuit	Non-stabilized Bias Network	Voltage Feedback Bias Network Feedback	Voltage Feedback w/Current Source Bias Network	Voltage Feedback w/Voltage Source Bias Network	Emitter Feedback Bias Network
Ic(mA) @ minimum h_{FE}	3.14	3.63	3.66	4.53	4.70
Ic(mA) @ typical h_{FE}	5.0	5.0	5.0	5.0	5.0
Ic(mA) @ maximum h_{FE}	9.27	7.09	6.98	5.44	5.27
Percentage change in Ic from nominal Ic	+85% -37%	+42% -27%	+40% -27%	+9% -9%	+5.4% -6%

Bias circuit #5 offers best control on h_{FE} variation but requires emitter resistor
Bias circuit #4 offer best control on h_{FE} variation without the use of an emitter resistor
Bias circuits #2 and #3 are very similar in performance.

Use of Stability Factors

$$I_{CBO} = \frac{\partial I_C}{\partial I_{CBO}} \quad h_{FE}, V'_{BE} = \text{constant}$$

$$V'_{BE} = \frac{\partial I_C}{\partial V'_{BE}} \quad I_{CBO}, h_{FE} = \text{constant}$$

$$h_{FE} = \frac{\partial I_C}{\partial h_{FE}} \quad I_{CBO}, V'_{BE} = \text{constant}$$

$$\Delta I_C = SI_{CBO} \bullet \Delta I_{CBO} + SV'_{BE} \bullet \Delta V'_{BE} + Sh_{FE} \bullet \Delta h_{FE}$$

First Calculate the stability factors for V'_{BE}, I_{CBO}, and h_{FE}. Then, to find the change in collector current at any temperature, multiply the change from 25°C of each temperature dependent variable with its corresponding stability factor and sum.

Calculating ΔI_{CBO}, $\Delta V'_{BE}$, and Δh_{FE}

Example: Calculate deltas from +25° C to +65° C

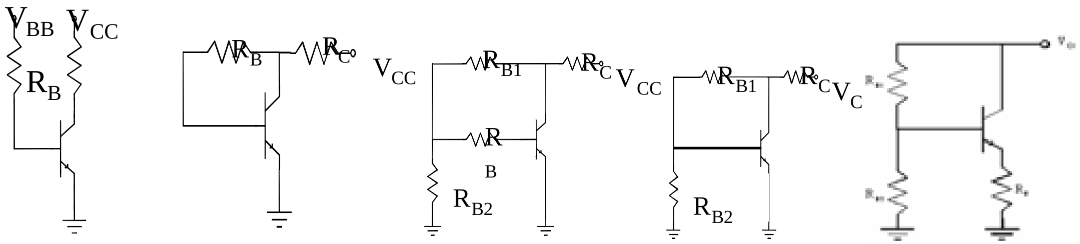
I_{CBO} is typically 100nA @+25° C and typically doubles for every 10°C temperature rise. Therefore I_{CBO} = 1600nA @ +65° C. ΔI_{CBO} = 1600 - 100 = 1500 nA

V'_{BE} measured at .755V@ 25° C and has a typical negative temperature coefficient of -2mV/°C. Therefore V'_{BE} will be .675V @ +65° C making $\Delta V'_{BE}$ equal to .675 - .755 = -.08V

h_{FE} is 80 @ +25° C and typically increases 0.5%/ ° C. Therefore h_{FE} will increase from 80 to 96 @ +65° C making Δh_{FE} equal to 96 -80 = 16

AVAGO TECHNOLOGIES

Bias Stability Analysis @ +65°C using HBFP-04XX



Bias Circuit	#1 Non-Stabilized	#2 Voltage Feedback	#3 Voltage Feedback w/Current Source	#4 Voltage Feedback	#5 Emitter Feedback
I_{CBO} Stability Factor	81	52.238	50.865	19.929	11.286
V'_{BE} Stability Factor	$-2.56653\text{x} 10^{-3}$	$-2.568011\text{x}10^{-3}$	$-3.956\text{x}10^{-3}$	-0.015	$-6.224378\text{x}10^{-3}$
h_{FE} Stability Factor	$6.249877\text{x}10^{-5}$	$4.031\text{x}10^{-5}$	$3.924702\text{x}10^{-5}$	$1.537669\text{x} 10^{-5}$	$8.707988\text{x}10^{-6}$
ΔI_C due to I_{CBO} (mA)	0.120	0.078	0.076	0.030	0.017
ΔI_C due to V'_{BE} (mA)	0.210	0.205	0.316	1.200	0.497
ΔI_C due to h_{FE} (mA)	0.999	0.645	0.628	0.246	0.140
Total ΔI_C (mA)	1.329	0.928	1.020	1.476	0.654
Percentage change in Ic from nominal Ic	26.6%	18.6%	20.4%	29.5%	13.1%

Bias Circuits
#1 non-stabilized
#2 volt feedback
#3 volt feedback w/current source
#4 voltage feedback
#5 emitter feedback

Bias circuits #2 and #3 similar in performance at temp and superior to #1 and #4
Bias circuit #5 is superior but requires emitter resistor and emitter bypass

Calculating ΔI_{CBO}, $\Delta V'_{BE}$, and Δh_{FE}

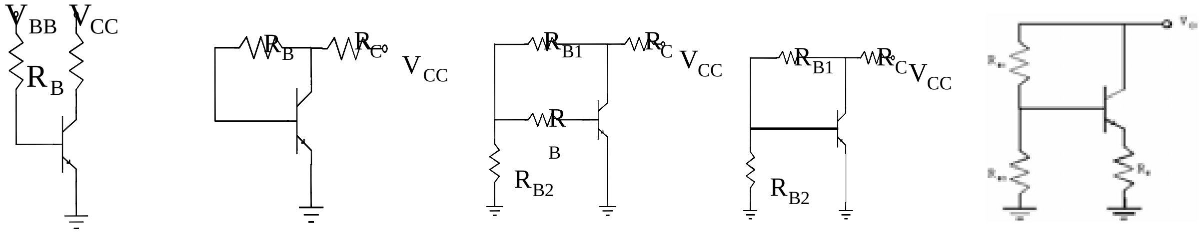
Example: Calculate deltas from +25° C to +85° C

I_{CBO} is typically 200nA @+25° C and typically doubles for every 10°C temperature rise. Therefore I_{CBO} = 12800nA @ +85° C. ΔI_{CBO} =12800 - 200 = 12600 nA= 12.6 uA

V'_{BE} measured at .755V@ 25° C and has a typical negative temperature coefficient of -2mV/°C. Therefore V'_{BE} will be .635V @ +85° C making $\Delta V'_{BE}$ equal to .635 - .755 = -.120V

h_{FE} is 150 @ +25° C and typically increases 0.5%/ ° C. Therefore h_{FE} will increase from 150 to 195 @ +85° C making Δh_{FE} equal to 195 - 150 = 45

Bias Stability Analysis @ +85ºC using HBFP-04XX

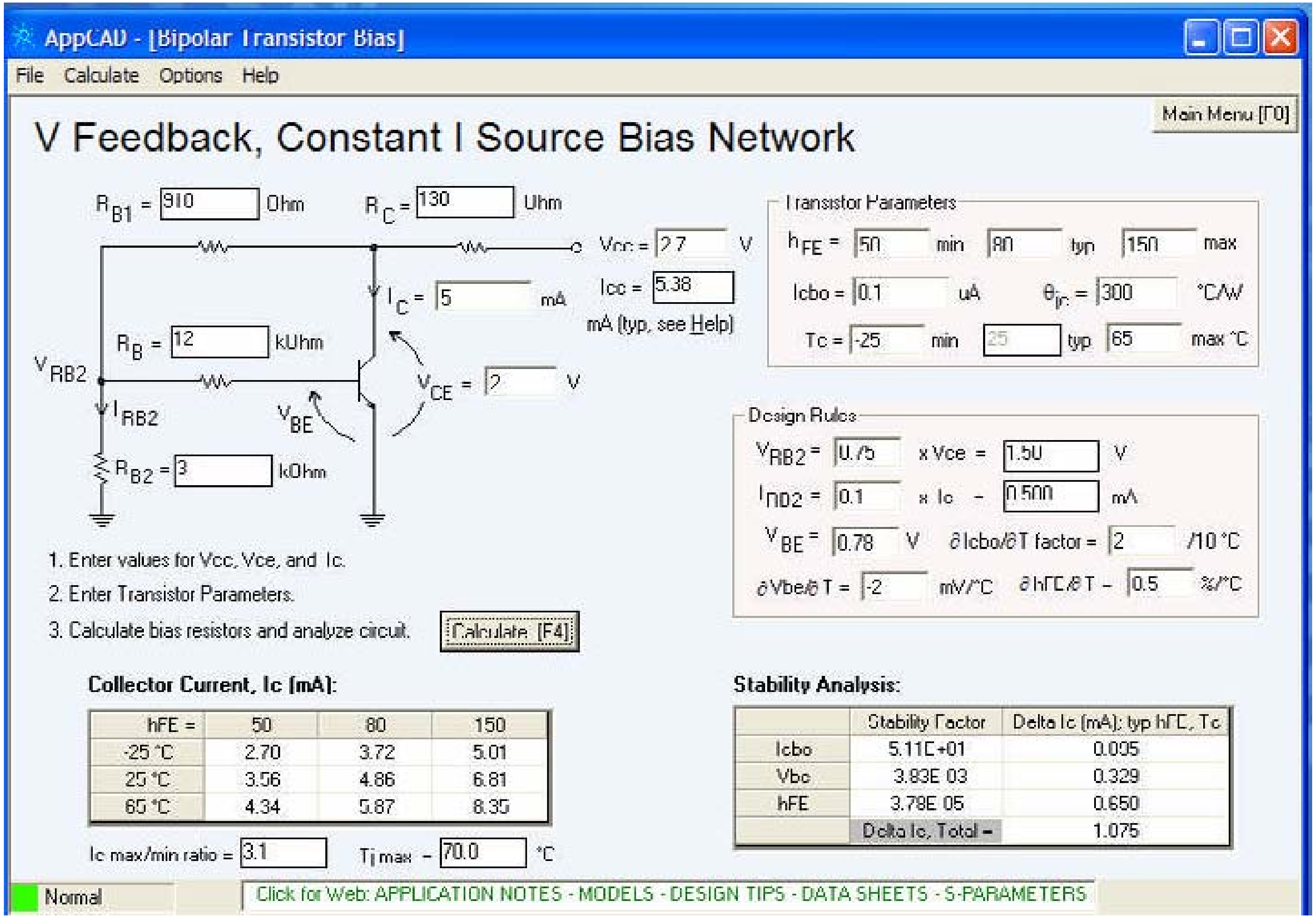


Bias Circuit	#1	#2	#3	#4	#5
I_{CBO} Stability Factor	81	52.238	50.865	19.929	11.286
V'_{BE} Stability Factor	$-2.56653\text{x } 10^{-3}$	$-2.568011\text{x}10^{-3}$	$-3.956\text{x}10^{-3}$	-0.015	$-6.224378\text{x}10^{-3}$
h_{FE} Stability Factor	$6.249877\text{x}10^{-5}$	$4.031\text{x}10^{-5}$	$3.924702\text{x}10^{-5}$	$1.537669\text{x}10^{-5}$	$8.707988\text{x}10^{-6}$
ΔI_C due to I_{CBO} (mA)	1.021	0.658	0.641	0.251	0.142
ΔI_C due to V'_{BE} (mA)	0.308	0.308	0.475	1.800	0.747
ΔI_C due to h_{FE} (mA)	2.812	1.814	1.766	0.692	0.392
Total ΔI_C (mA)	4.141	2.780	2.882	2.743	1.281

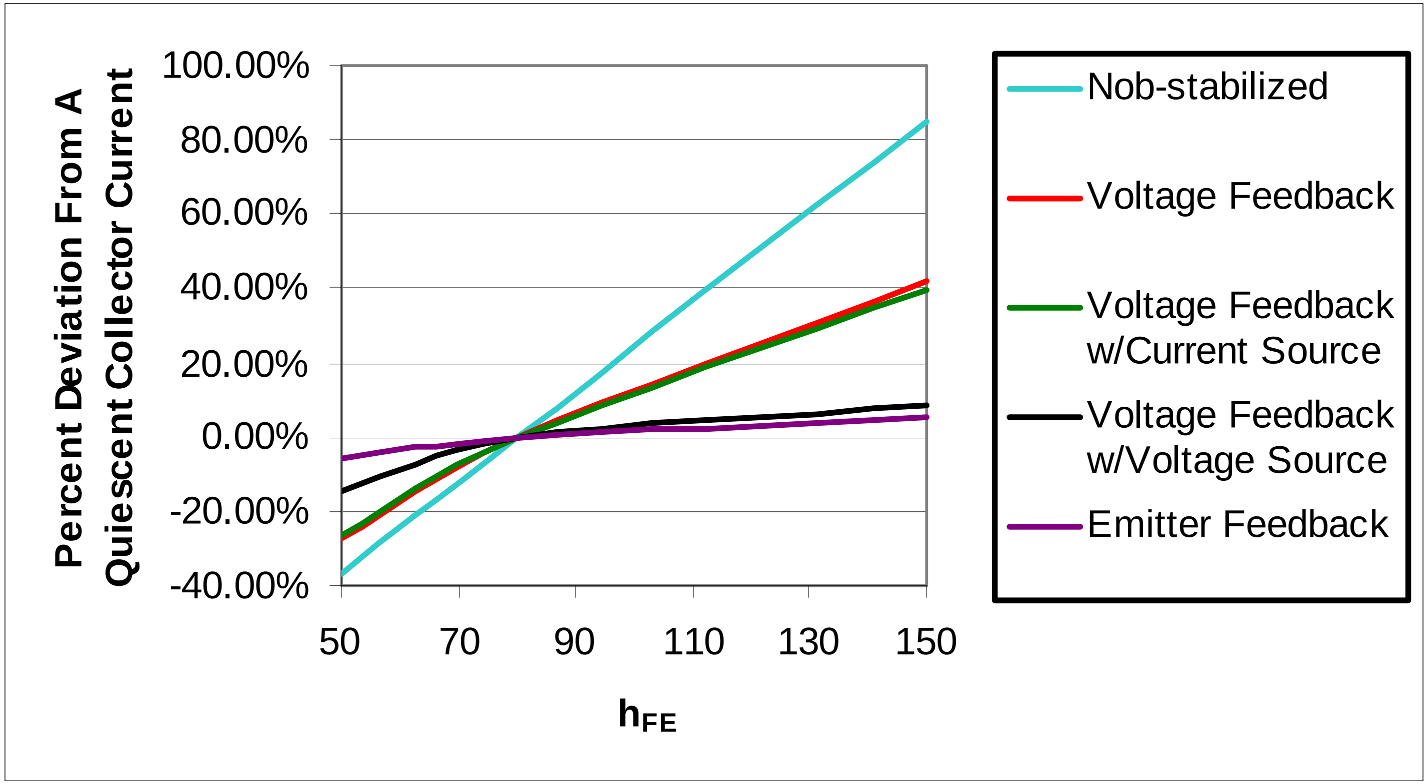
Bias Circuits
#1 non-stabilized
#2 volt feedback
#3 volt feedback w/current source
#4 voltage feedback
#5 emitter feedback

Bias circuits #2, #3 and #4 similar in performance at temp and superior to #1
Bias circuit #5 is superior but requires emitter resistor and emitter bypass
I_{CBO} and h_{FE} variations are major contributors at elevated temperature

Avago Technologies AppCAD

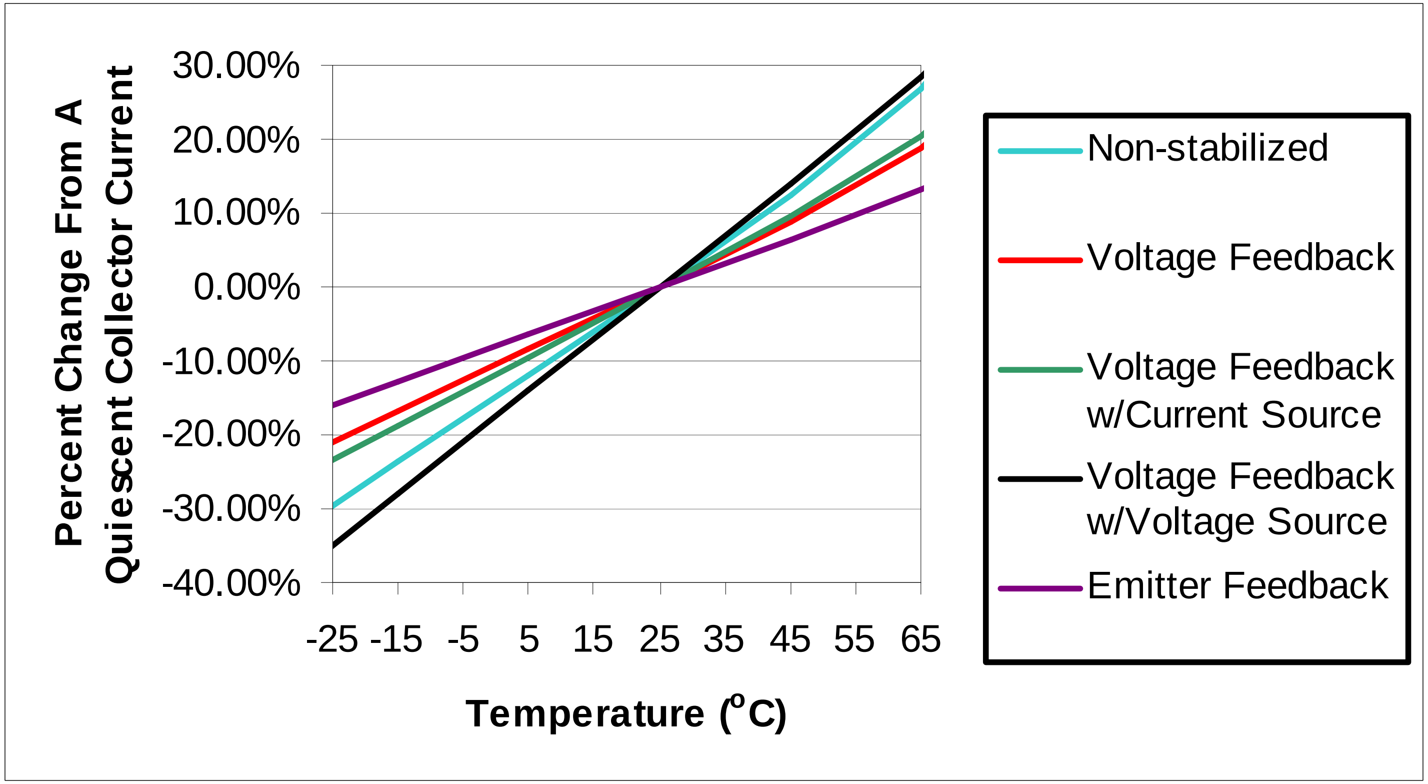


Percent Change in Quiescent Collector Current versus h_{FE} for the HBFP-0405



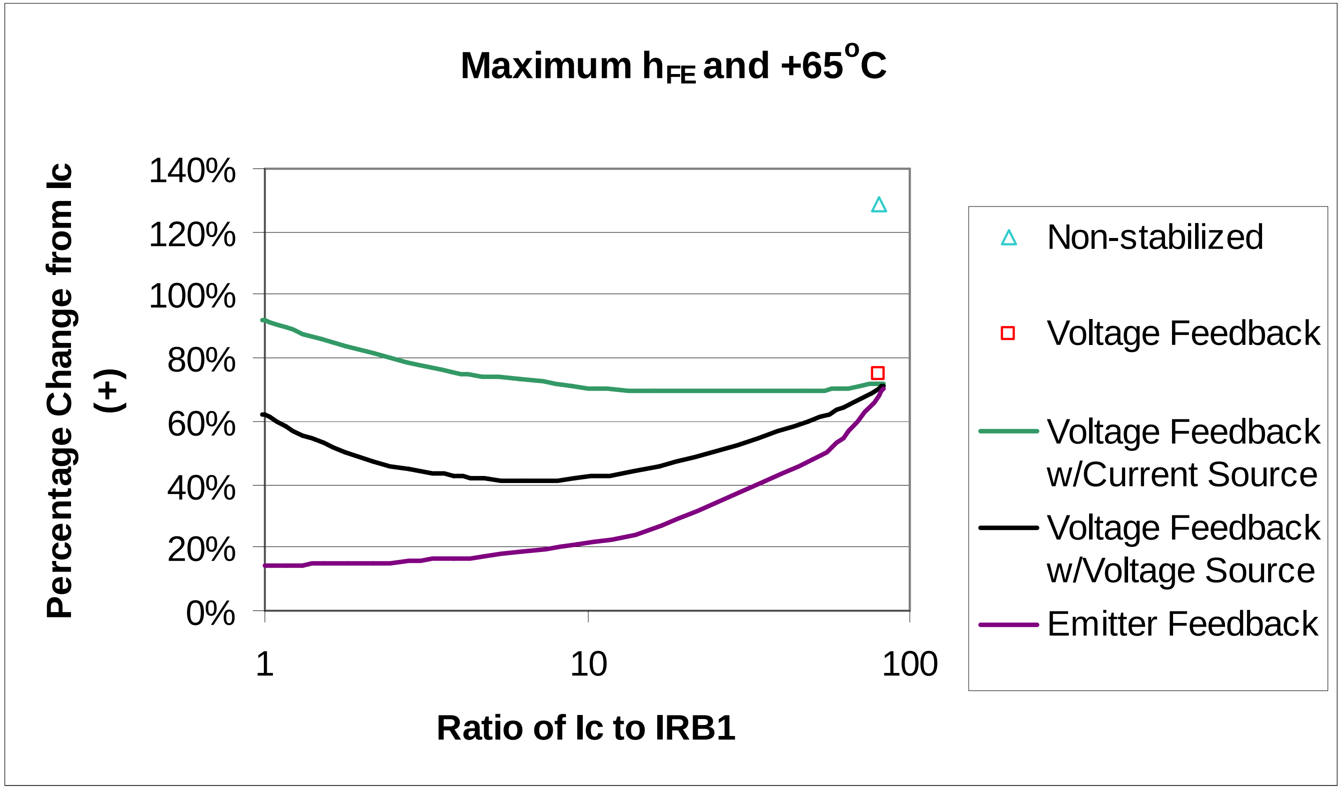
V_{CC}=2.7V
V_{CE}=2V
I_C=5 mA
T_J=+25°C

Percent Change in Quiescent Collector Current versus Temperature for the HBFP-0405



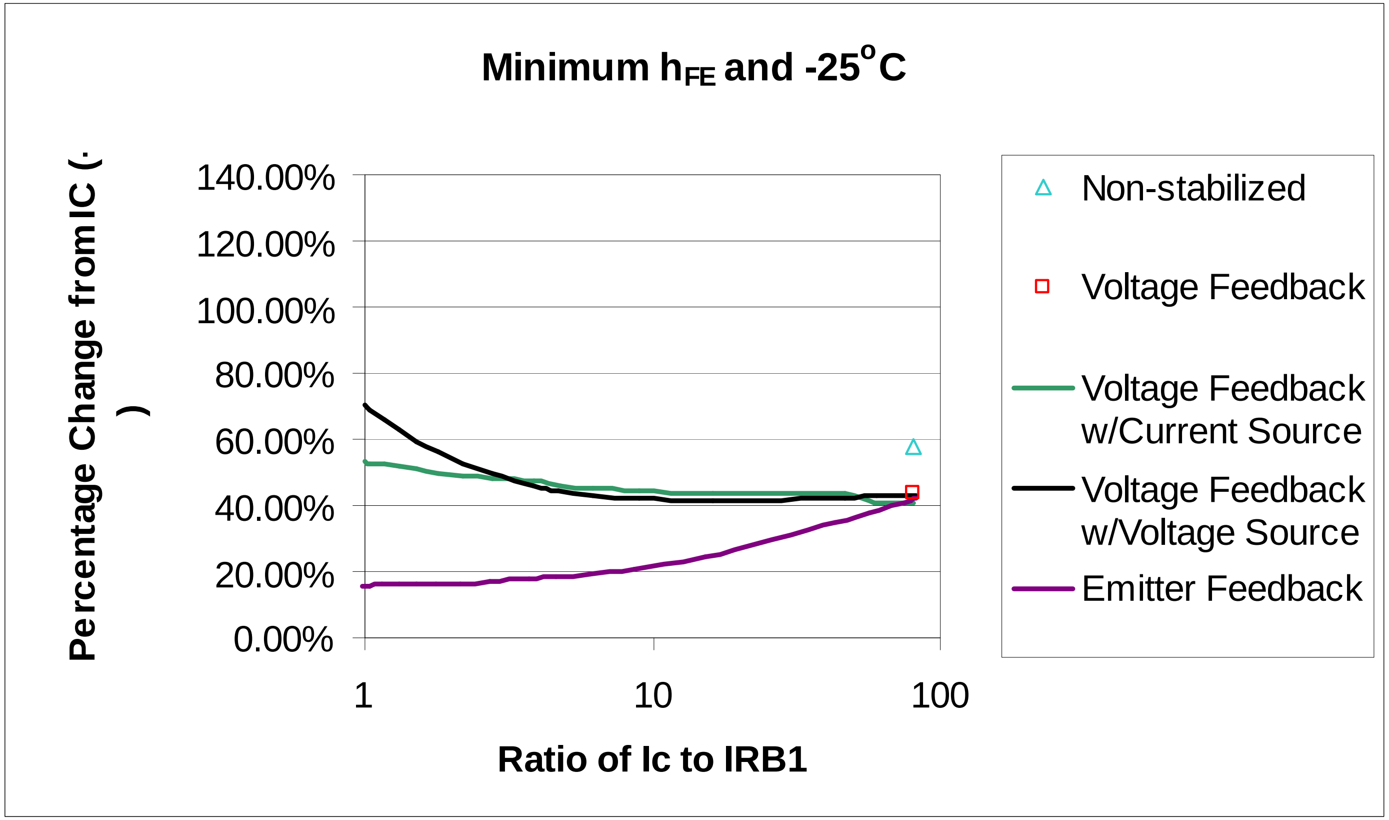
V_{CC}=2.7V
V_{CE}=2V
I_C=5 mA

Percent Change in Quiescent Collector Current versus Ratio of I_C to I_{RB1} for Max. h_{FE} and +65°C for the HBFP-0405



V_{CC}=2.7V
V_{CE}=2V
I_C=5 mA

Percent Change in Quiescent Collector Current versus Ratio of I_C to I_{RB1} for Min. h_{FE} and -25°C for the HBFP-0405



V_{CC}=2.7V
V_{CE}=2V
I_C=5 mA

Conclusions

Emitter feedback in circuit #5 offers the best control on h_{FE} variations from device to device and over temperature. However, an emitter bypass capacitor is needed to provide a good RF short. The inductance associated with the bypass capacitor quite often causes circuit instabilities with high f_t transistors.

Best alternative is circuit #4 followed by circuit #2. Circuit #4 offers best control on h_{FE} variation from device to device and circuit #2 provides best performance up to +65 degrees C. At +85 degrees C, circuit #4 performs as well as circuit #2.

Additional Thoughts

Higher Vcc can improve the performance of all bias circuits

Additional base bias resistor current can often improve bias regulation

An increase in the value of the emitter resistor for circuit #5 will offer increased bias circuit regulation.

Active bias network offers best regulation but requires additional components.

Related Application Notes and Articles

AN 1084 Two-Stage 800 – 1000 MHz Amplifier using the AT-41511 Silicon Bipolar Transistor – 5964-3853E (11/99)

AN 1085 900 and 2400 MHz Amplifiers using the AT-3 Series Low Noise Silicon Bipolar Transistors – 5964-3854E (11/99)

AN 1131 Low Noise Amplifiers for 320 MHz and 850 MHz Using the AT-32063 Dual Transistor – 5966-0781E (11/99)

AN 1293 A Comparison of Various Bipolar Transistor Biasing Circuits – 5988-6173EN June 27, 2006

AN S014 750 – 1250 MHz Voltage Controlled Oscillators – 5988-0273EN (9/00)

A Comparison of Various Bipolar Transistor Biasing Circuits by Al Ward (W5LUA) and Bryan Ward (N5QGH), Agilent Technologies, Applied Microwave & Wireless, April 2001, pages 30-44