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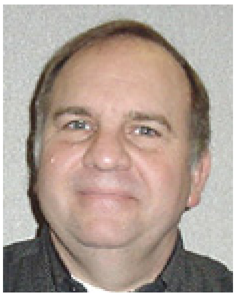
Practical aspects of feedback control

Originally broadcast on January 22, 2004

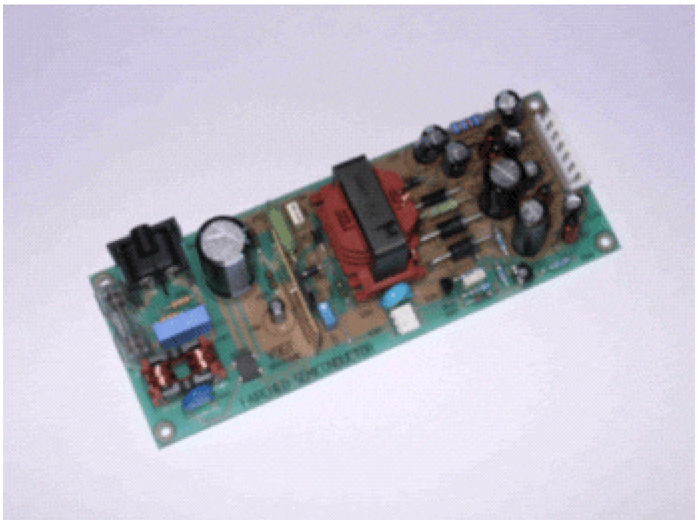


Bob Krause
Applications Engineering Manager
Optoelectronic Business Unit
Fairchild Integrated Circuits Group, ICG

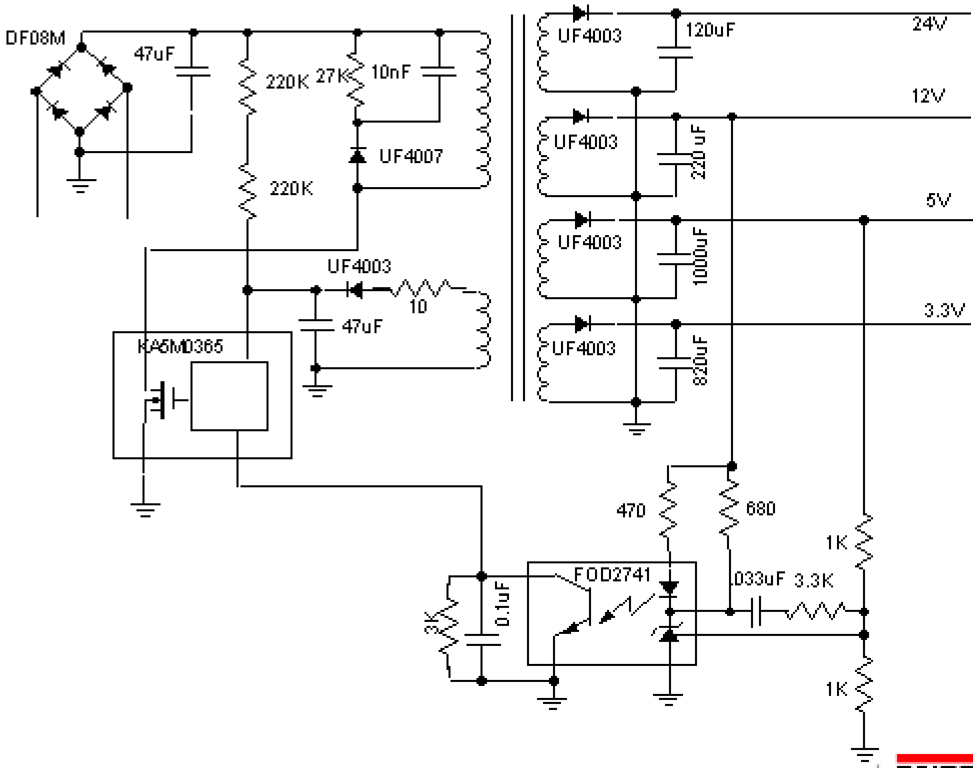
Presentation Overview:
This webcast explains design considerations when using an optically isolated error amplifier as the voltage feedback device in an off-line switch mode power supply. Using a practical example, the primary focus is on understanding what determines the frequency response of the feedback control system, with the goal of ensuring control loop stability and acceptable transient response in an isolated power supply.

About the Presenter:
Bob Krause is the Applications Engineering Manager of the Optoelectronic Business Unit of Fairchild Integrated Circuits Group, ICG. During Bob's thirty years of optoelectronic experience he has held applications management positions at the optoelectronic divisions of Hewlett Packard, General Instruments, Siemens, Infineon , and Vishay. He is a holder of 8 US patents, has authored numerous trade articles, and design application notes, plus is co-author of text book "Optoelectronics – Fiber Optic Applications Manual"

Practical design of FPS Feedback Control



FPS Multi-output Flyback Schematic

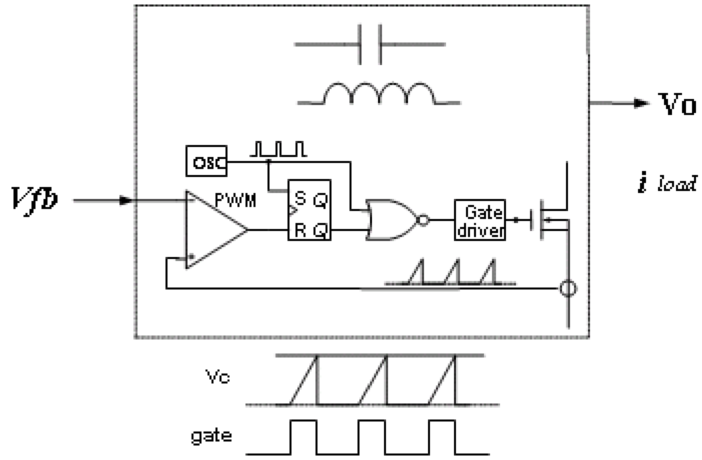


OUTLINE – SMPS Feedback Control

1. Control Loop Elements
   - Controller
   - Feedback Amplifier
2. DC Isolation Amplifier Operation
   - DC Gain Analysis
   - AC Frequency Analysis
3. Error Amplifier Operation
   - DC Gain analysis
   - AC Response
4. Open & Closed Loop Measurement
   - Techniques
   - Results

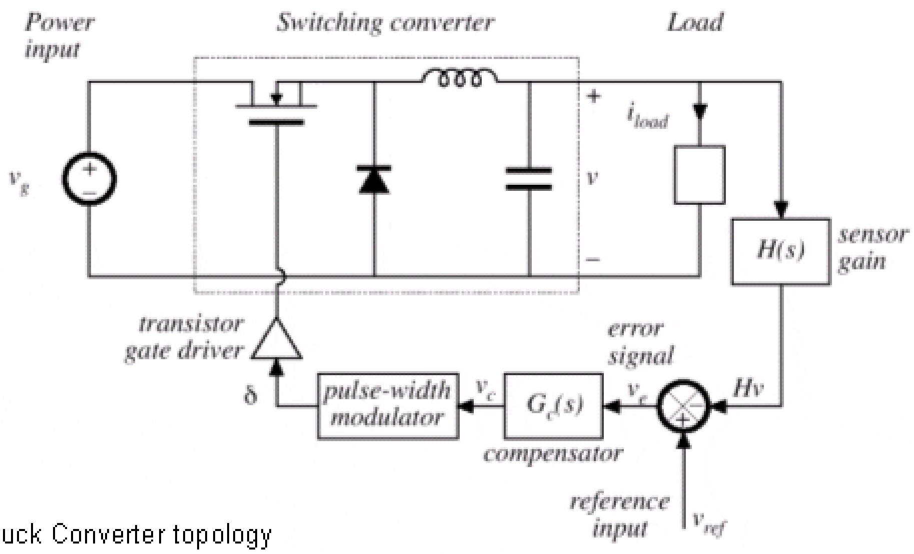
Current mode converter – FPS- KA5M10365

Switching converter



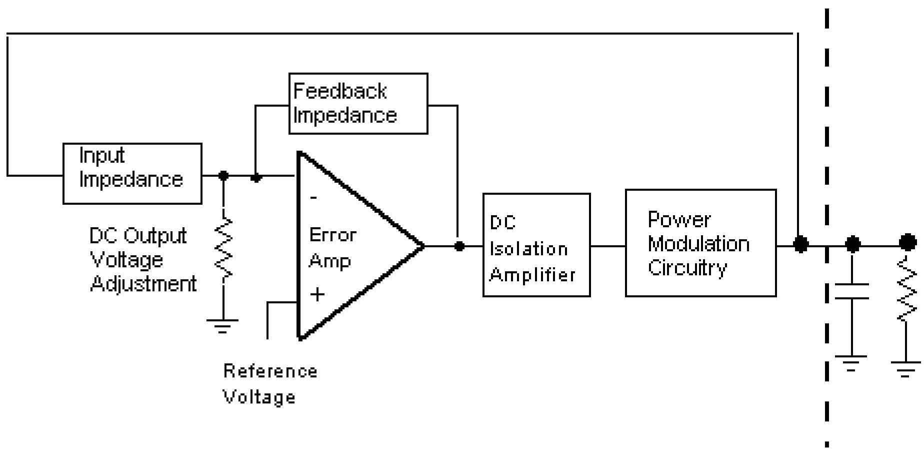
FPS - How does it work?

A walk around the loop



Buck Converter topology

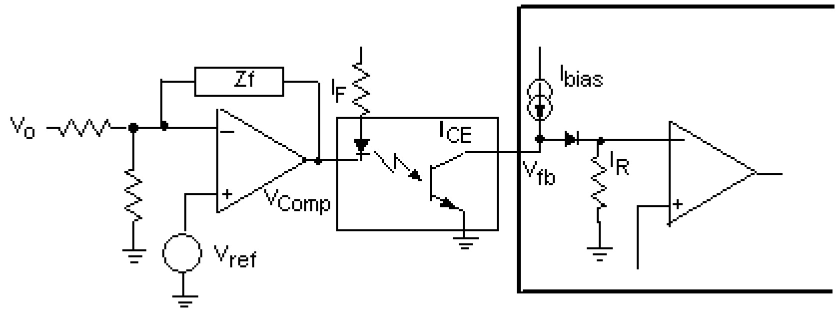
SMPS Feedback Amplifier



Feedback Amplifier includes DC Isolation Amplifier, and the Voltage Error amplifier.

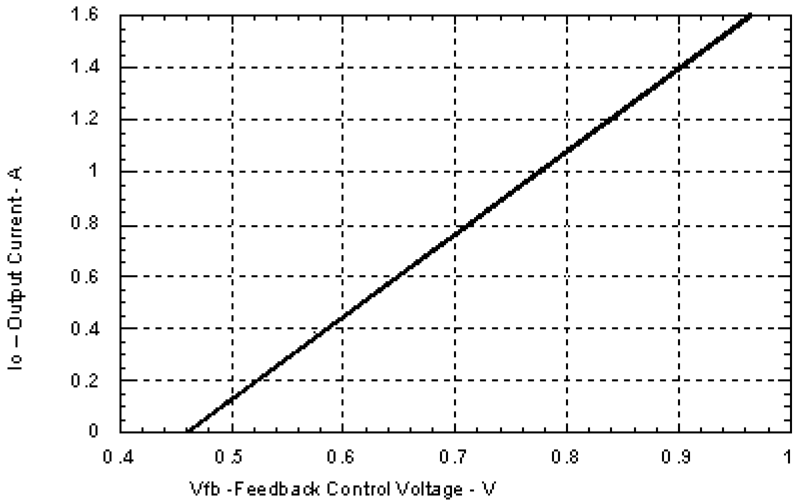
How does it work?

A walk around the Feedback loop



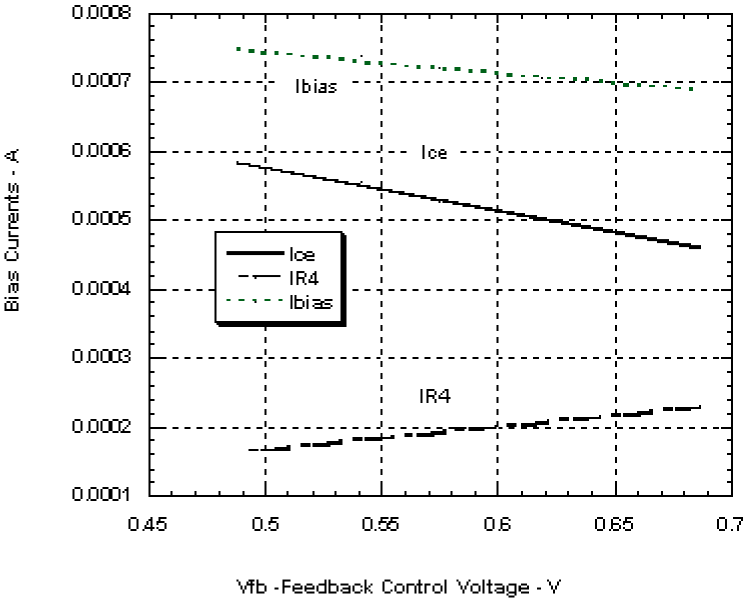
↑	↓	↑	↓	↓	↑	↑
I_L	V_o	V_{Comp}	I_F	I_{CE}	I_R	V_{fb}
Load Current	Output Voltage	Comp Voltage	LED Current	Collector Current	Resistor Current	Feedback Voltage

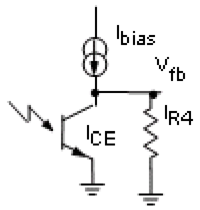
KA5M0365 DC Feedback Control



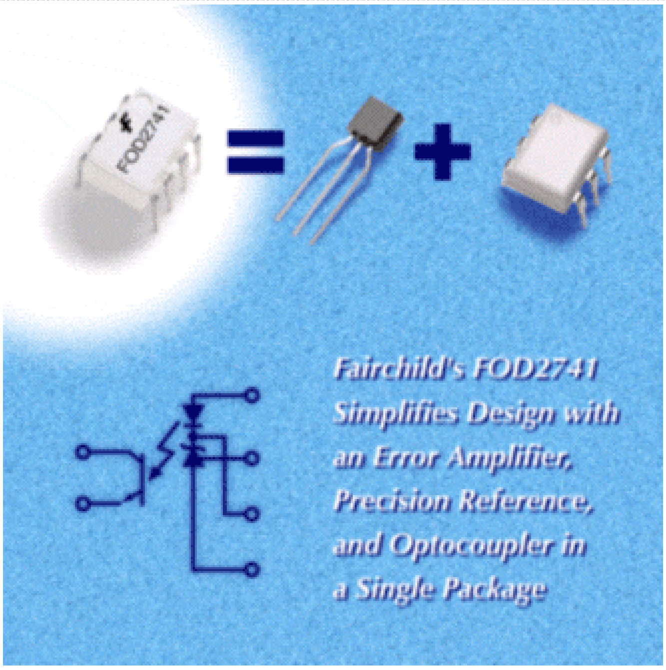
These represent the DC transfer curves for the KA5M0365 when the supply is providing a constant 5 volt output.

Feedback Voltage vs Control Current

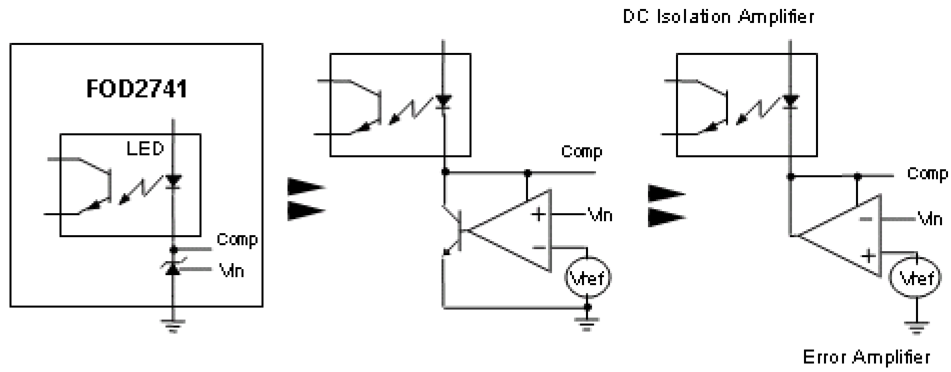




Optical Coupled Precision Voltage Reference

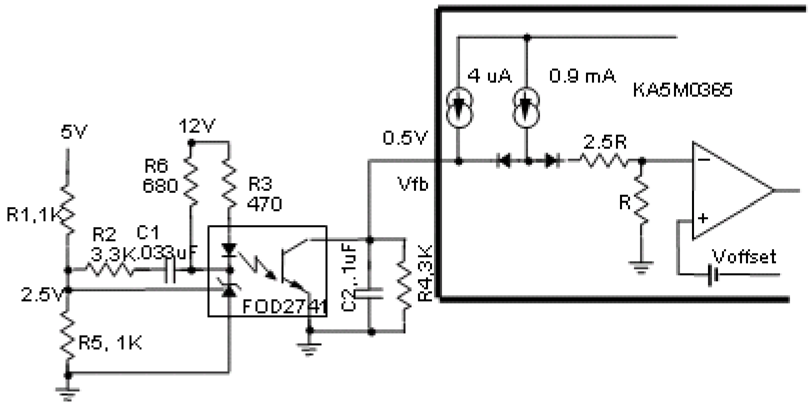


Feedback Amplifier
FOD2741 Composition



The FOD2741/2 consists of adjustable precision zener diode and a phototransistor optocoupler. Typical Current gain , CTR, is 60% for an IF = 1 mA, and Vce = 0.5V.
The device offers a 2.5V +- 1% bandgap reference, a 60dB (OLG) 1 MHz(BWP) differential amplifier.

Feedback Amplifier Interconnection



The resistor and capacitor values shown are used though out the following analysis.
These are used in the demo board supporting the KA5M0365

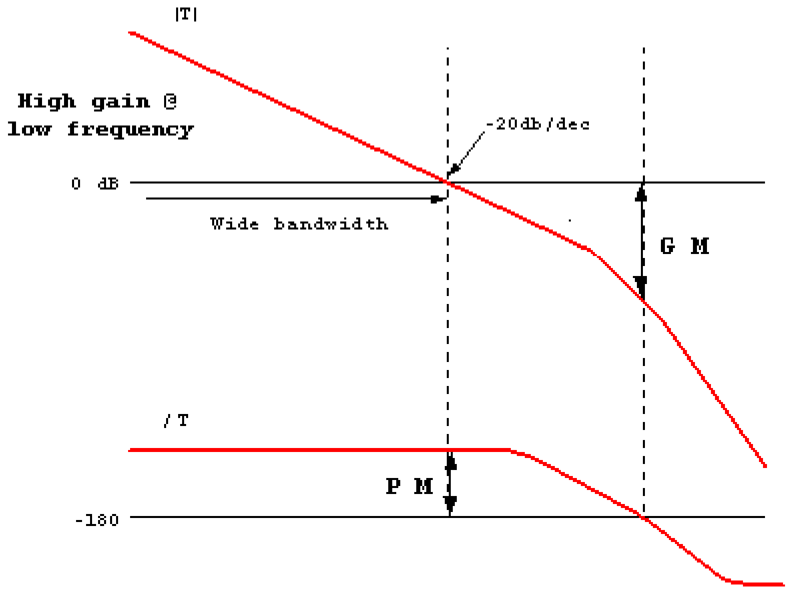
Stability
– Gain Margin, Phase Margin and band width

Gain Margin
- Gain is changed according to the variation of circuit components
- Related to robustness against gain variation

Phase Margin
- Related to the damping of the system.
- Low PM causes oscillatory transient response

Bandwidth
- Related to the speed of transient response

Stability – Desired loop gain characteristics



Feedback Amplifier Types

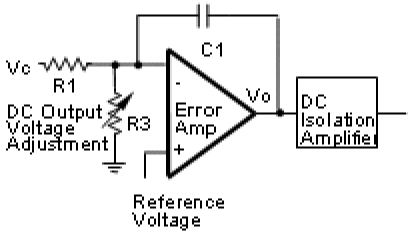
Each of these amplifier types offer different levels of Phase boast in the Feedback amplifier. Increasing the phase and gain margin is the key task of the feedback amplifiers compensation function

Type 1 Single Pole – No phase boast

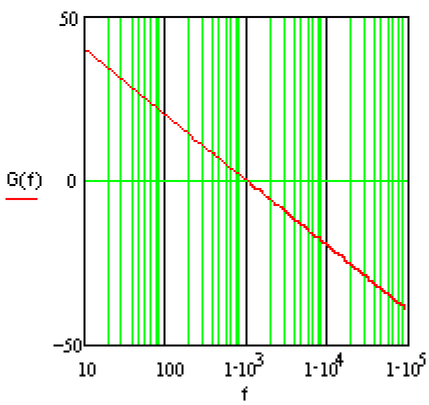
Type 2 Two poles, 1 zero Up to 90 degrees

Type 3 Two Poles, 2 zeros Up to 180 degrees

Type 1 Compensation Circuit



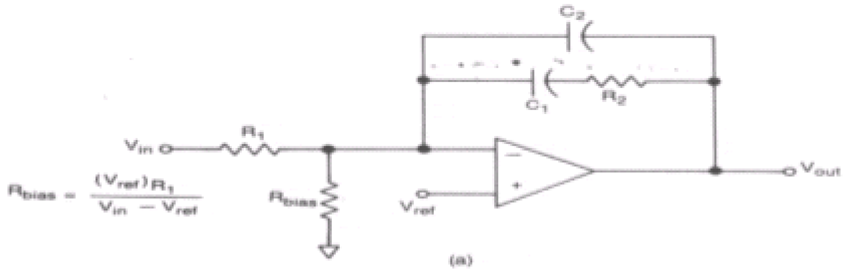
Phase shift = 90 degrees



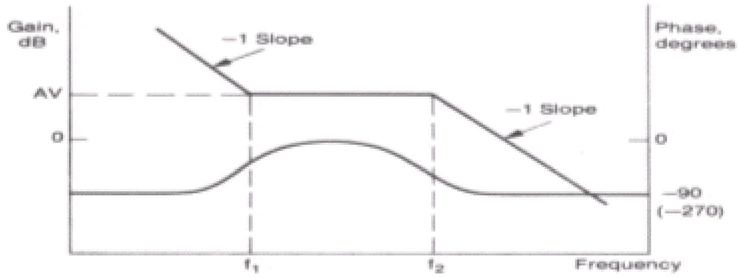
$$G(f) := 20 \cdot \log\left(\frac{1}{s(f) \cdot C1 \cdot R1}\right)$$

Type 2 Gain and Phase Boast

$$G(f) := 20 \cdot \log\left[\frac{(R2 \cdot s(f) \cdot C1 + 1)}{(s(f) \cdot (R1 \cdot (R2 \cdot s(f) \cdot C1 \cdot C2 + C2 + C1)))}\right]$$

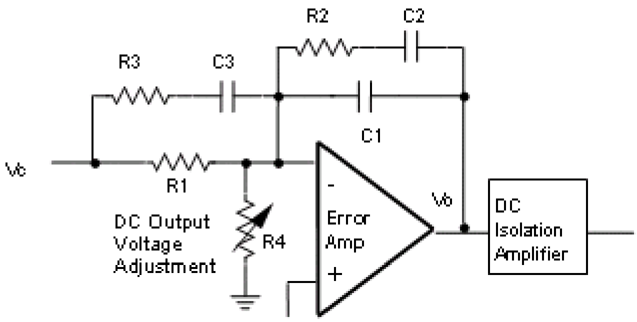


(a)



(b)

Type 3 Schematic

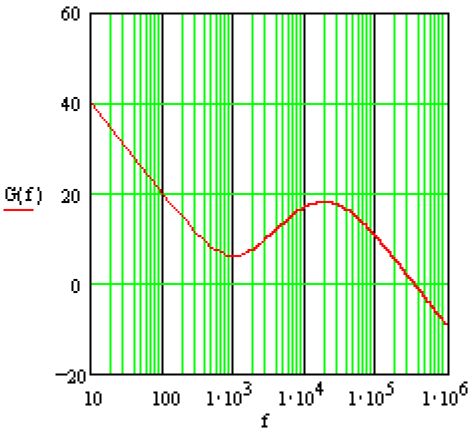


$$G(f) := 20\cdot\log\left[\frac{(R2\cdot s(f)\cdot C1+1)}{(s(f)\cdot((R2\cdot s(f)\cdot C1\cdot C2+C2+C1)\cdot(R1\cdot(R3\cdot s(f)\cdot C3+1))))}\cdot(R1\cdot s(f)\cdot C3+R3\cdot s(f)\cdot C3+1)\right]$$

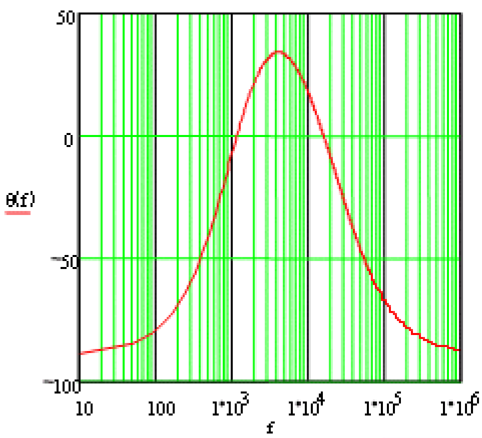
TYPE 3 Bode Plot

$$G(f) := 20\cdot\log\left[\frac{(R2\cdot s(f)\cdot C1+1)}{(s(f)\cdot((R2\cdot s(f)\cdot C1\cdot C2+C2+C1)\cdot(R1\cdot(R3\cdot s(f)\cdot C3+1))))}\cdot(R1\cdot s(f)\cdot C3+R3\cdot s(f)\cdot C3+1)\right]$$

Frequency Response



Phase Response



DC Isolation Amplifier

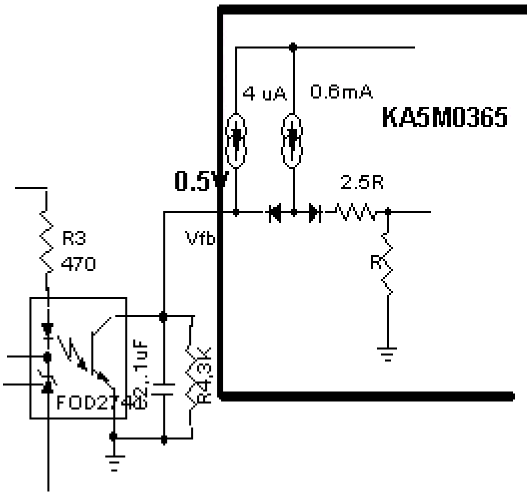
The feedback voltage , Vfb, is found at the node composed of the input of the controller, the phototransistor's collector, and the low pass filter (R4 and C2). The KA5M0365 offers an internal current source, Ibias, measured to be 600 uA.This is used to develop the control voltage Vfb. The nodal equation is:

0 = Ibias - Ice - I(Z2)

Ice is the phototransistor's collector emitter current

I(Z2) is the current through the parallel combination of R4 and C2.

s(f) = jω = j2πf .



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0 = Ibias - Ice - I(Z2)

Ice is the photransistor collector emitter current

I(Z2) is the current throught the parallel combination of R4 and C2.

$$Z2(f) := \frac{1}{\left(\frac{1}{R4} + s(f)\cdot C2\right)} \longrightarrow Z2(f) := \frac{R4}{(s(f)\cdot C2\cdot R4 + 1)}$$

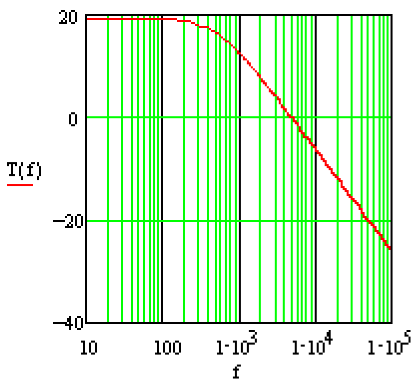
DC Isolation amplifier Gain And Phase Response

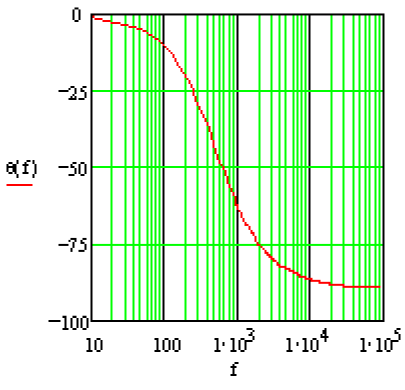
$f := 10, 50 .. 100000 \qquad s(f) := 2\cdot\pi\cdot f\cdot j$

$IF := .006 \quad Ib := 0.0006 \quad CTR := .60 \quad R4 := 3000 \quad C2 := 0.1\cdot 10^{-6}$

$$Z2(f) := \frac{R4}{(s(f)\cdot C2\cdot R4 + 1)}$$

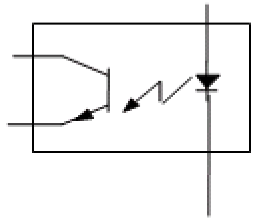
$$T(f) := 20\cdot\log((Ib - CTR\cdot IF)\cdot Z2(f)) \qquad \theta(f) := \frac{180}{\pi}\cdot\arg((Ib - CTR\cdot IF)\cdot Z2(f)\cdot -1)$$





Optocoupler's Temperature Performance

The DC isolation amplifier includes an Infrared LED and an NPN phototransistor

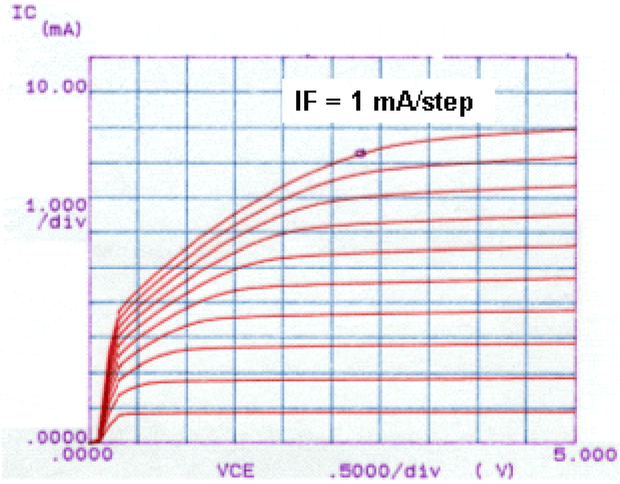


The light output of the LED is temperature dependent , it has a negative temperature coefficient of approximately –1%/C. Thus as the junction temperature increases the light output will be reduced. The Feedback Amplifier control loop compensates for this drop by increasing the LED current to force the output phototransistor to sink the required Ice to keep the DC output level , Vo, constant.

The phototransistor gain is also temperature dependant. However in the FPS system the device is driven at a low collector emitter voltage (Vce = 0.3 to 1V) , and small collector current Ice . Under this condition the transistor's gain variation is also compensated by the operation of the Feedback amplifier.

DC gain variation of the DC Isolation Amplifier is insured by adding an additional 6 dB gain margin to the feedback loop.

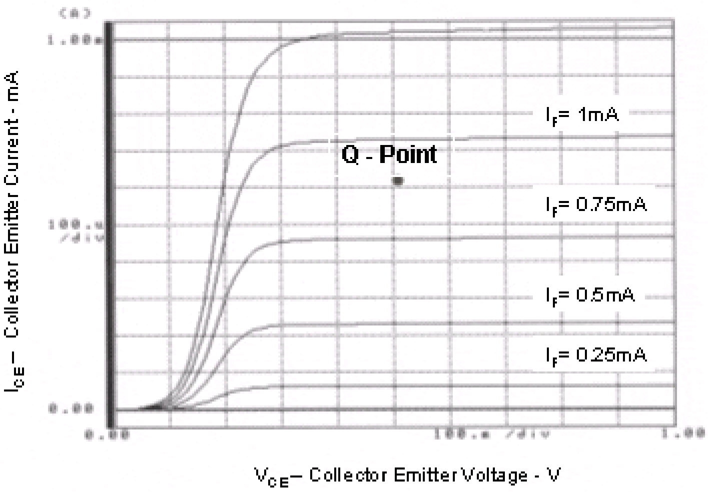
DC Isolation Amplifier
Phototransistor Transfer Family



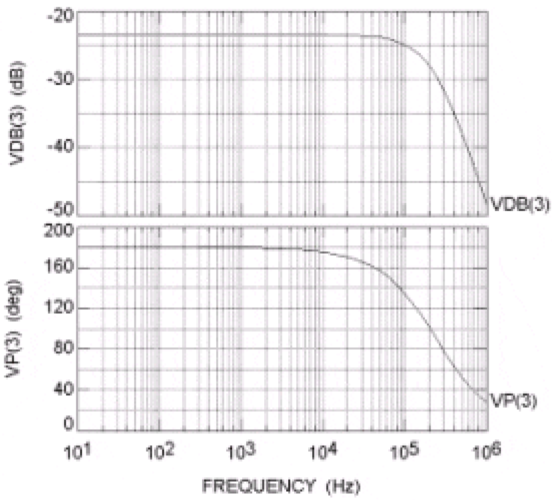
The typical phototransistor is specified with a forward LED of 10 mA and a Vce of 10 V . The KA5M0365 Typically operates with a Vce less than 1 V and an Ice of between 500 uA and 1 mA.

Low Current Characteristic of FOD274X

Q-point : I_{CE} = 570uA, V_{CE} = 0.493V, I_F = 860uA, CTR_{CE} = 66%

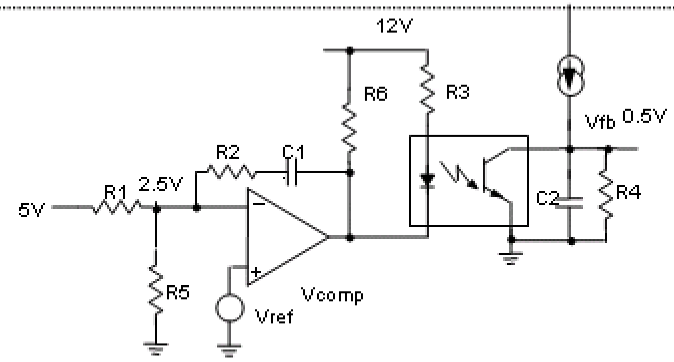


Frequency and Phase Response of the FOD274X's Phototransistor



These two curve point out the small signal Frequency and phase response of the phototransistor found in the FOD274X family.

Error Amplifier Operation



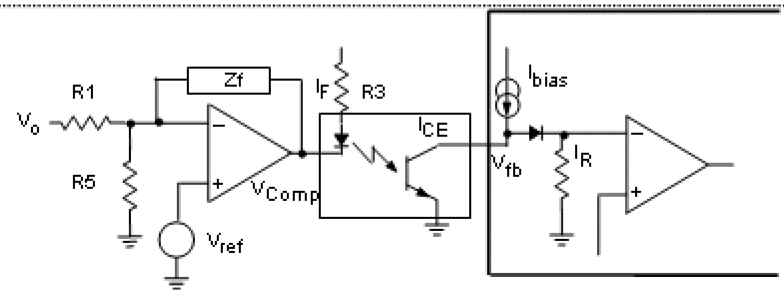
The error consists of the operational amplifier, a compensation network R2 and C1, the voltage reference, voltage divider used to set the supply voltage (R1 & R5) , and the coupler current gain setting resistor R3. The resistor R6 functions as a zener bias source.

The circuit evaluated was set for a operational voltage of 5V. Given that the reference is 5V, R1 = R5. The precise resistor values are determined from the compensation design process.

The LED current , IF, is determined by the error amplifier output voltage , Vcomp, divided by R3.

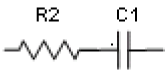
The error amplifier offers a low frequency 180 degree phase shift, Thus as the supply voltage sags under load The Vcomp rises, resulting in a reduction in LED current . A reduction in LED current causes a lower phototransistor Ice.

Error Amplifier Gain



$$\frac{Vcomp(f)}{Vo} := \frac{Zf(f)}{R1}$$

Zf

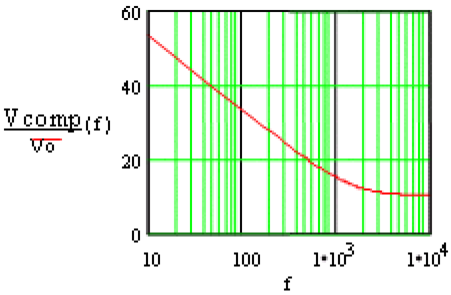


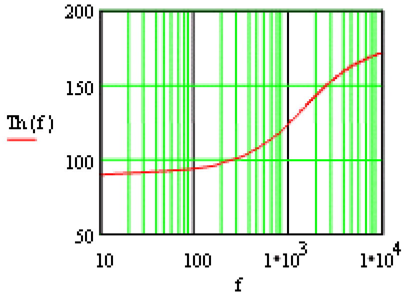
$$Zf(f) := R2 + \frac{1}{s(f)\cdot C1} \qquad Zf(f) := \frac{(R2\cdot s(f)\cdot C1 + 1)}{(s(f)\cdot C1)}$$

$$\frac{Vcomp}{Vo}(f) := \frac{\frac{R2\cdot s(f)\cdot C1 + 1}{s(f)\cdot C1}}{R1} \qquad \frac{Vcomp}{Vo}(f) := \frac{(R2\cdot s(f)\cdot C1 + 1)}{(s(f)\cdot(C1\cdot R1))}$$

Error Amplifier Gain and Phase

$$\frac{Vcomp}{Vo}(f) := 20 \cdot \log\left[\frac{(R2 \cdot s(f) \cdot C1 + 1) \cdot -1}{(s(f) \cdot (C1 \cdot R1))}\right] \qquad Th(f) := \frac{180}{\pi} \cdot \arg\left[\frac{(R2 \cdot s(f) \cdot C1 + 1) \cdot -1}{(s(f) \cdot (C1 \cdot R1))}\right]$$





Feedback Amplifier response

1.Feedback Amplifier Gain

Vcomp is the output of the error amplifier
Vo is output voltage of the power supply and the input to the error amplifier

$$V_{comp}(f) := -\frac{Zf(f) * V_o}{R1}$$

$$Zf(f) := R2 + \frac{1}{s(f) \cdot C1} \qquad Zf(f) := \frac{(R2\, s(f)\, C1 + 1)}{(s(f) \cdot C1)}$$

$$\frac{V_{comp}}{V_o}(f) := -\frac{\frac{R2 \cdot s(f) \cdot C1 + 1}{s(f) \cdot C1}}{R1} \qquad \frac{V_{comp}}{V_o}(f) := \frac{-(R2 \cdot s(f) \cdot C1 + 1)}{(s(f) \cdot (C1 \cdot R1))}$$

2. LED current , IF

$$IF(f) := \frac{V_{comp}(f)}{R3}$$

Feedback Amplifier Response- Error Amplifier and DC Isolation Amplifier

LED Current as a function of the Error Amplifier output signal

$$IF(f) := \frac{-(R2 s(f) \cdot C1 + 1) * V_o}{(s(f) \cdot (C1 (R1 R3)))}$$

Load network of the DC isolation Amplifier

$$Z2(f) := \frac{R4}{(s(f) \cdot C2 R4 + 1)}$$

Feedback Voltage at the output of the DC Isolation Amplifier

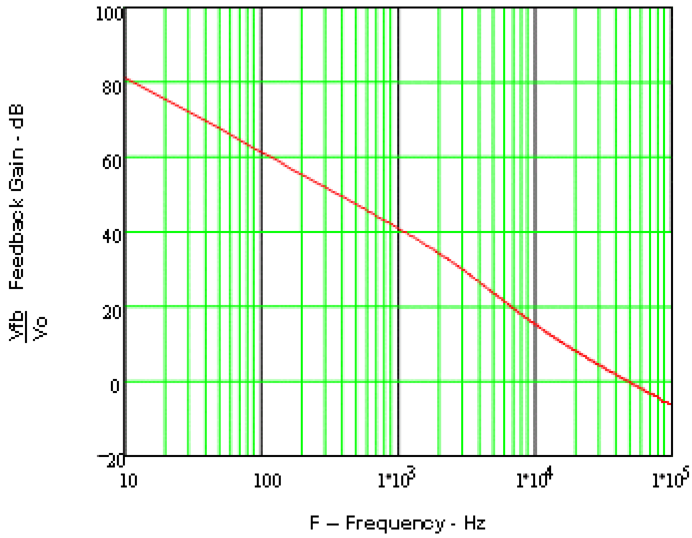
$$Vfb(f) := (Ib - CTR \cdot IF(f)) \cdot Z2(f) \qquad CTR = .6$$

Final transfer function of the Feedback Amplifier

$$\frac{Vfb}{V_o}(f) := \left[Ib - CTR \frac{-(R2 s(f) \cdot C1 + 1)}{(s(f) \cdot (C1 (R1 R3)))} \right] \frac{R4}{(s(f) \cdot C2 R4 + 1)}$$

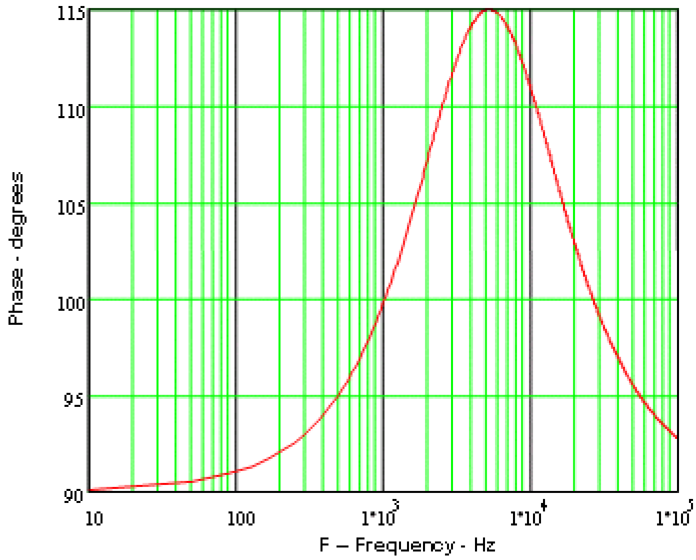
Calculated Feedback Amp Frequency Response

$$\frac{Vfb}{Vo}(f) := 20\log\left[(Ibs(f)\cdot C1\cdot R1\cdot R3 + CTR\cdot R2\cdot s(f)\cdot C1 + CTR)\cdot\frac{R4}{(s(f)\cdot(C1\cdot(R1\cdot(R3\cdot(s(f)\cdot C2\cdot R4 + 1)))))}\right]$$

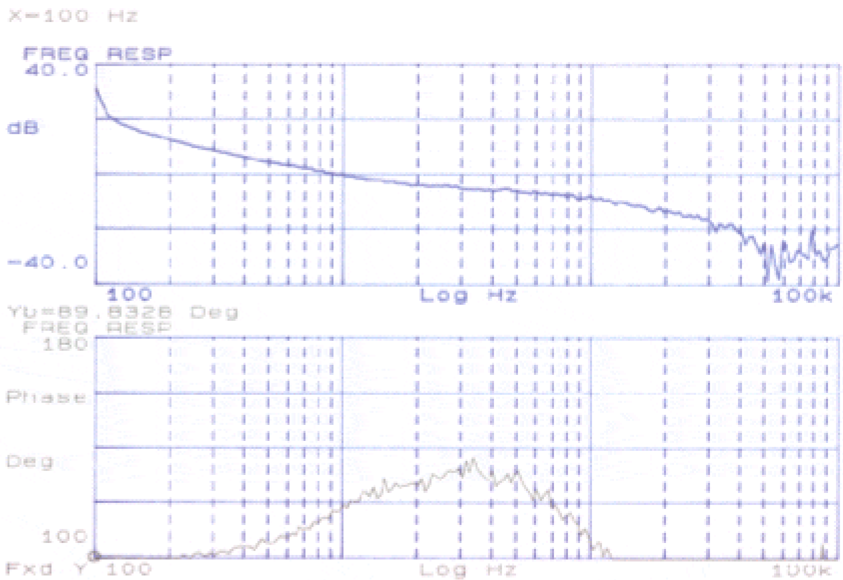


Calculated Phase Response – Feedback Amplifier

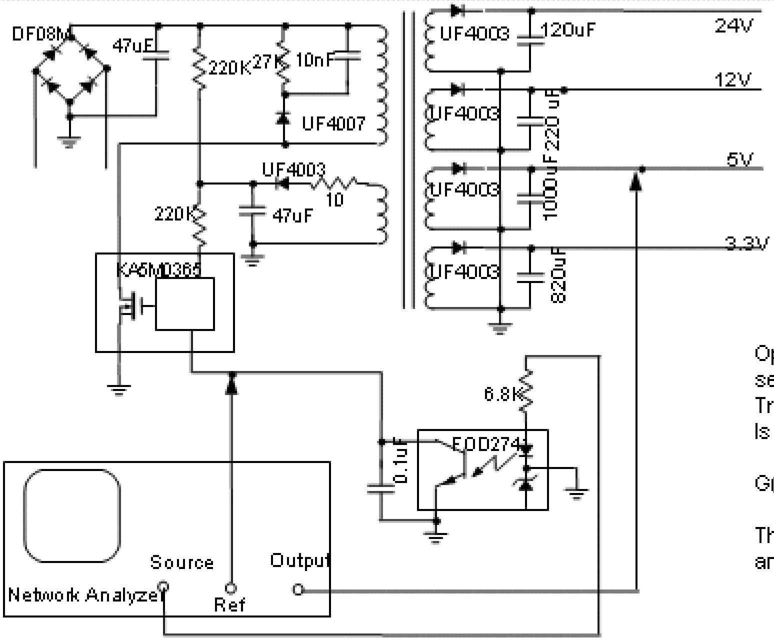
$$\mathbf{Phase}(f) := \frac{-180}{\pi} \cdot \arg\left[(Ibs(f) \cdot C1R1R3 + CTRR2s(f) \cdot C1 + CTR) \cdot \frac{R4}{(s(f) \cdot (C1(R1(R3(s(f) \cdot C2R4 + 1)))))} \right]$$



KA5M0365 Feedback Amplifier – Measured



Open Loop Gain Signal Injection

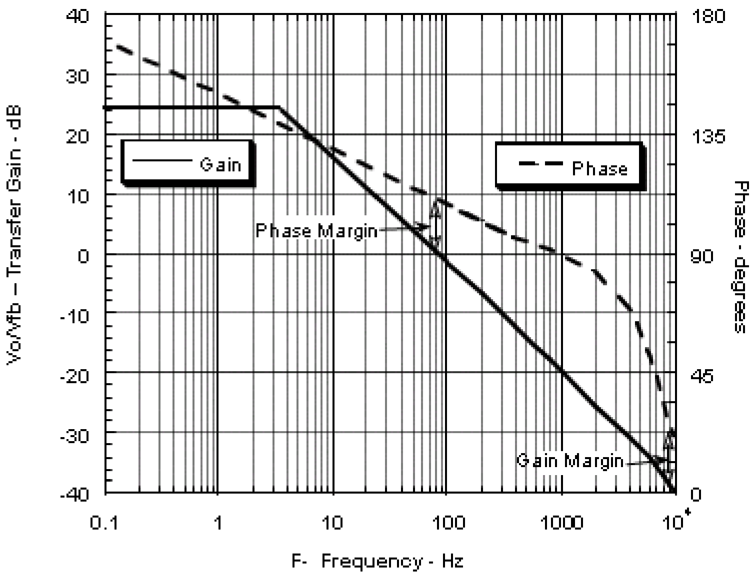


Optocoupler provides the DC level setting and small signal injection.
Transfer Gain
Is the ratio of the Output to the Input

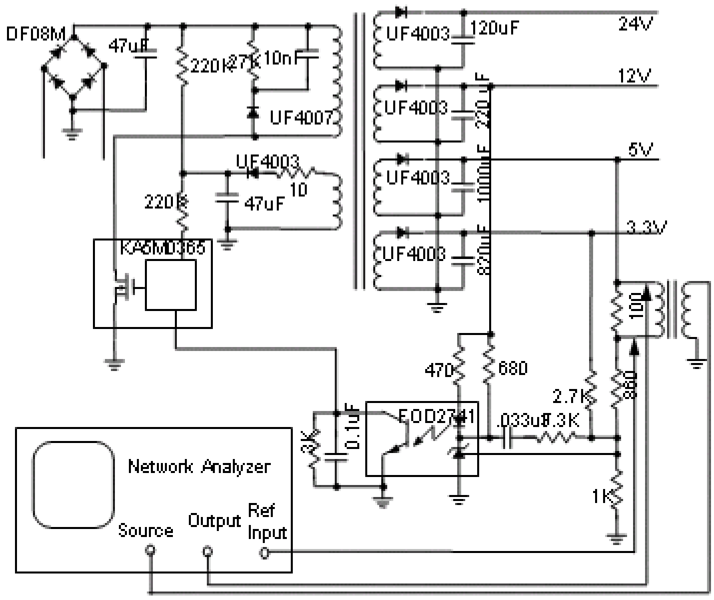
G(s) = 20log(Vo/Vfb)

The regulator is biased for Vfb = 0.5V, and a current of 600 uA.

KA5M0365 – Open Loop Response



Loop Gain Analysis Test Circuit



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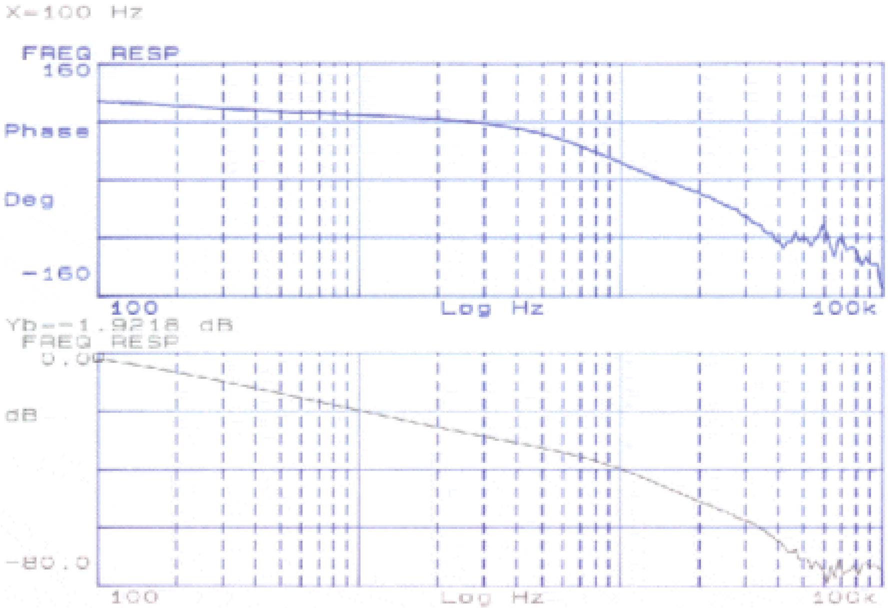
KA5M0365 –Loop Gain Response



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