

## 10MHz ANALOG MULTIPLIER CARRIES OUTPUT AMP, BREAKS BANDWIDTH BARRIER

**A transconductance multiplier chip, the first one fitted with an output amplifier, alleviates design worries in high-bandwidth communication circuits.**

Beyond a 1MHz bandwidth, multiplier chips usually need external amplifiers and biasing, and many cannot deliver their promised accuracy and performance without external trimming components. Those burdens have largely kept single-chip multipliers out of communication applications. Mixer circuits, for example, have instead relied on signal-diode rings, even though those rings bring their own performance drawbacks, including poor low-frequency response and narrow frequency and power ranges.

With the introduction of the MPY634 multipliers, wideband analog multiplication need no longer be a multichip affair or imply performance compromises. Along with its 10MHz small-signal bandwidth, the four-quadrant chip has a laser-trimmed DC accuracy of 0.25%, an adjustable scale factor, and the ability to drive loads down to 2kΩ.

In addition, because it has three instead of two differential input pairs, the chip can divide, square, and find square roots. Those functions make it, in effect, a multifunction converter. As a result, adding just a few components creates any number of analog processors, including a voltage-controlled filler or a mixer.

The chip unites three voltage-to-current input converters, a transconductance core, a highly stable voltage reference, and a high-gain output amplifier (Figure 1). The three converters can be viewed as differential amplifiers with an extremely low transconductance. The benefits of which are a 10MΩ input impedance and a 20V/μs slew rate. Moreover, the converters' input voltages can be differential or single-ended; in the latter case, the second input can be used to nullify offsets.

### HAVING THE DRIVE

The differential outputs of the converters drive the transconductance core, which actually performs the multiplication. The output of the core, a differential current, produces a voltage across a resistive load that feeds a high-gain, high-bandwidth amplifier. For multiplication, the output of the amplifier is fed back to converter Z; other mathematical operations are set up by different feedback connections.

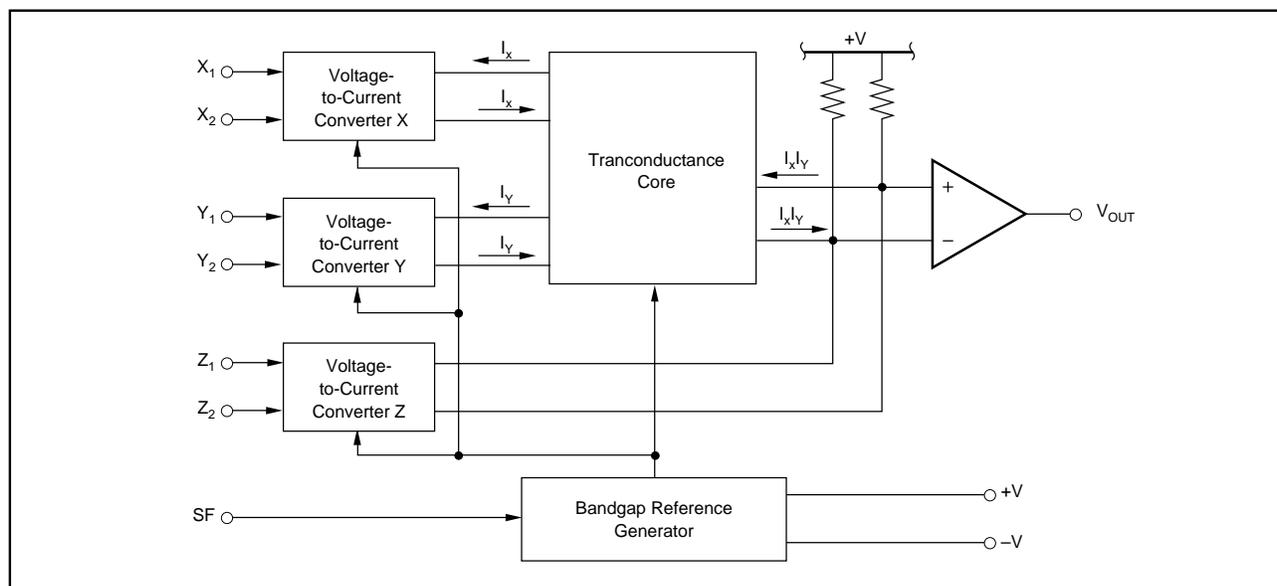


FIGURE 1. The MPY634 Multiplier Chip is the First to Break the 1MHz Barrier. Without the external wideband amplifier, a suitable alternative to diode mixers. It combines three voltage-to-current converters, a transconductance core, a voltage reference, and an output amplifier.

Like any mathematical circuit, the multiplier is only as good as its linearity, accuracy, and stability. Here linearity and accuracy depend on the transconductance core, and more specifically, on how precisely the base-to-emitter voltages of its six transistors match. To maximize linearity, the transistors are diagonally coupled (cross-coupled) on the die and then laser-trimmed.

Maintaining a constant scale factor over temperature requires stable bias current in the core. A built-in bandgap reference keeps the scale factor's temperature coefficient within 30ppm/°C over a temperature range of -55°C to +125°C. Nevertheless, the scale factor can be adjusted over the range of 10V to 3V by connecting a resistor from the negative supply to the Scale Factor Adjust pin.

As with an op amp, the multiplier's open-loop equation offers insight into the chip's operation, as well as into its constraints. The open-loop equation is:

$$V_{OUT} = A \left[ \frac{(X_1 - X_2)(Y_1 - Y_2)}{SF} - (Z_1 - Z_2) \right]$$

where:

$V_{OUT}$  is the output voltage;

A is the output amplifier's open-loop gain and is assumed to be infinite;

$X_N$ ,  $Y_N$ , and  $Z_N$  are input voltages;

SF is the scale factor, which is nominally 10V.

For stability, feedback is applied to one or more inputs. (However, when feedback involves more than one input, designers must take care that the overall feedback does not become positive.) Since the gain is always positive, inputs that receive feedback become dependent on the output voltage. Thus, the behavior of the circuit can be predicted by substituting  $V_{OUT}$  (or its function) for the appropriate input voltage.

For example, in a basic multiplier with single-ended inputs and no offset,  $X_2$ ,  $Y_2$ , and  $Z_2$  all equal zero. Feedback enters directly through the  $Z_1$  input. Because converter Z drives the output amplifier's inverting input, the feedback is negative and the output voltage is given by:

$$V_{OUT} = A (X_1 Y_1 / SF - V_{OUT})$$

When A approaches infinity, the equation gives:

$$V_{OUT} = X_1 Y_1 / SF$$

Applying the feedback through a voltage divider increases the overall gain. For example, if a 10:1 attenuator makes  $Z_1$  equal  $0.1V_{OUT}$ , as gain becomes infinite the open-loop equation becomes

$$V_{OUT} = 10 X_1 Y_1 / SF$$

To make a divider circuit, single-ended inputs  $X_2$ ,  $Y_1$ , and  $Z_2$  are grounded. The feedback is applied to  $Y_2$  so that it is negative for positive values of  $X_1$ . However, if  $X_1$  is negative, then  $Y_2$  is grounded and the feedback is applied to  $Y_1$ . In either case, the open-loop equation is:

$$V_{OUT} = A \left[ \frac{(X_1)(-V_{OUT})}{SF} - Z_1 \right]$$

As gain approaches infinity,  $V_{OUT}$  becomes  $Z_1 / X_1 SF$ .

The scope of the multiplier chip becomes apparent in a highly accurate voltage-controlled filter. Two multiplier chips, a universal active filter chip, four resistors, and six bypass capacitors team up to form a second-order filter with high-pass, low-pass, and bandpass outputs (Figure 2). The multipliers act like linear voltage-controlled resistors that set the filter's center frequency and thus the cutoff frequency of the high- and low-pass outputs. Although the active filter chip allows a compact implementation for bandwidths up to 200kHz and a Q of up to 500, the bandwidth can be extended to 1MHz by implementing the filter with discrete op amps instead.

Precision 1% resistors ensure accurate values for the full-scale center frequency and for Q. Two such resistors, between each multiplier's output and the filter chip, determine the full-scale frequency, which is the center frequency of the bandpass for a 10V control voltage. In operation, a control voltage drives both multipliers at once and must always be greater than 0V. If the voltage falls to zero or goes negative, the feedback around the filter chip is lost and the circuit becomes unstable.

With 0.1% resistors, the filter holds its full-scale frequency to 2% over a 10:1 range of control. Moreover, no external trimming adjustments are required, unless accuracy must be raised even further (in which case the input offsets can be nulled by trimming). The bandpass and cutoff frequencies drift no more than  $\pm 50$ ppm/°C over -55°C to +125°C. At a full-scale frequency of 25kHz, the wideband noise is typically less than 160 $\mu$ V. The output swing can go as high as 20Vp-p, yielding a dynamic range of 96dB.

Limits on the slew rate of the amplifiers inside the universal active filter restrict the input amplitude and Q. First, since the filter's internal amplifiers handle a maximum slew rate of 10V/ $\mu$ s, the full power bandwidth (10Vpk) is 160kHz compared with the gain bandwidth product of 4MHz. As a result, the input voltage should be limited to 20Vp-p below 80kHz and 2Vp-p between 80 and 500kHz. Above that, the maximum input voltage is determined by the formula  $f_c / 50,000$ , where  $f_c$  is the filter's cutoff frequency. Second, a high Q can make internal voltages larger than the input swing. Thus the maximum Q is below 4kHz and  $f_c / 20,000$  above 4kHz.

The high performance of this voltage-controlled oscillator justifies the use of the multiplier and the universal active filter. Though a switched-capacitor filter and a voltage-controlled oscillator represent an easier and less costly alternative, the arrangement's 75dB dynamic range and 30kHz upper frequency fall far short of the multiplier-based configuration. Moreover, the switched-capacitor approach suffers from clock feedthrough and aliasing, which dictate additional filtering.

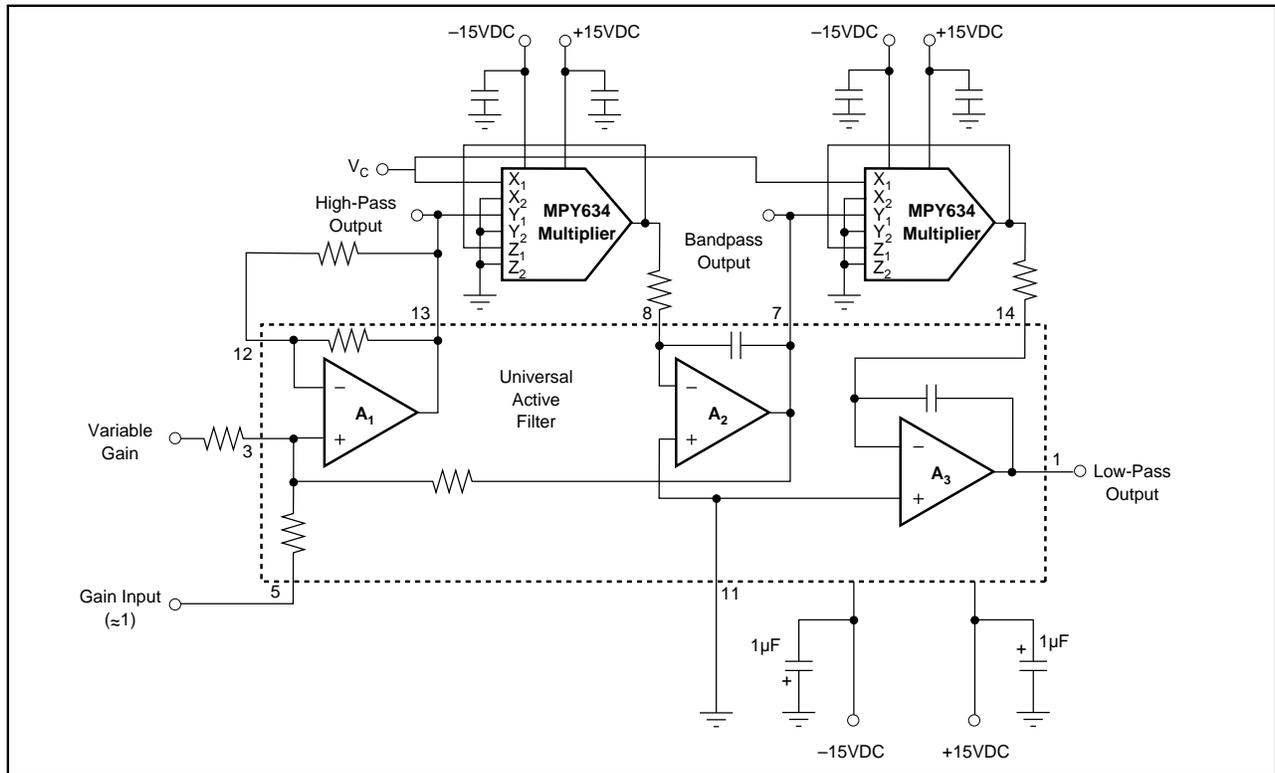


FIGURE 2. A Voltage-Controlled Second-Order Filter Revolves Around Two Multiplier Chips and a UAF42 Universal Active Filter. The multipliers act as linear voltage-controlled resistors that vary the center and cutoff frequencies of the active filter chip.

Since this transconductance multiplier needs no external circuitry to attain its wide bandwidth, it is a particularly good choice for building low-cost mixer circuits (see “Strike up the Bandwidth”). Mixers form the heart of heterodyning, which is used for modulating and demodulating signal amplitude.

A ring-diode circuit, one of the most common types of mixers, performs well at high frequencies but suffers numerous limitations. For instance, since the diodes in the ring must be biased, transformers must be coupled at the mixer’s input and sometimes at the output. Unfortunately, transformer coupling precludes low-frequency operation. The low-end frequency of most diode mixers is limited to several hundred kilohertz, preventing them from modulating RF signals directly with audio signals.

On the other hand, the transconductance mixer is directly coupled and thus can modulate audio signals directly onto an RF carrier. For example, the amplitude of a 10MHz carrier can be modulated simply by applying an audio signal to the X input of the multiplier chip and feeding the output of a 10MHz local oscillator to the Y input.

A ring-diode mixer also requires a resistive impedance, usually 50Ω, at its input and output ports. A reactive impedance can severely degrade performance. The transconductance mixer, in contrast, is relatively insensitive to I/O

impedances. At low frequencies, its input impedance is 10MΩ and, at about 1MHz, that starts to drop off, falling to a low of 25kΩ at 10MHz. If required, a 50Ω resistor can be shunted across the input to match impedances. The output is insensitive to load impedances greater than 2kΩ and less than 100pF.

Transconductance mixers exhibit better linearity than typical double-balanced diode mixers (see the table). The input voltage to diode mixers is applied directly to the diode junction, so that the region of linear operation is small. Any nonlinearity causes harmonic distortion and feedthrough, which adversely affect almost all specifications. In addition, it generates spurious carriers, intermodulation distortion, and increased feedthrough. Within the transconductance mixer, the input voltage is converted into a current before being applied to the core, affording a much wider range of linear operation.

One mixing application combines a 1kHz low-pass filter with a 5MHz local oscillator to create a bandpass filter with an extremely high Q of 5000—normally an impractical if not impossible achievement. In a passive network, reaching that Q would necessitate many poles, which are difficult and costly to tune. In addition, a typical active circuit version would require expensive op amps with high gain-bandwidth products.

The input signal is first multiplied by the local oscillator and then sent through the low-pass filter (Figure 3). Since the filter has a 1kHz bandwidth, it passes all incoming components between the local oscillator frequency and 1kHz above it. The filter's output is then reconverted into the original frequency by multiplying it by the local oscillator output. An image frequency is created when the signal is reconverted. The circuit can also translate the center frequency of a bandpass filter, a useful feature when the required filter falls outside of the commonly available communications frequencies.

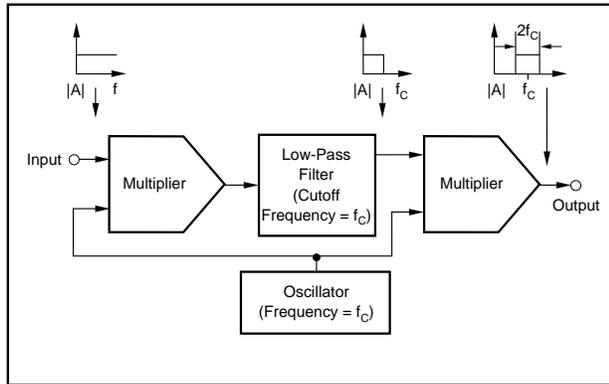


FIGURE 3. In a Frequency-Mixing Circuit, One Multiplier Chip Converts the Input Signal into DC, and Another Translates the DC Signal Back into the Original Frequency. With this technique, a 1kHz low-pass filter and a 5MHz local oscillator create a bandpass filter with an effective Q value of 5000 and a 5MHz center frequency.

The mixer circuit can also be adopted for phase detectors; the designer need only connect a low-pass filter to the multiplier chip's output (Figure 4). The configuration follows the principle that the product of two signals of equal frequency contains a DC component, and that component is proportional to the cosine of the angle between the signals.

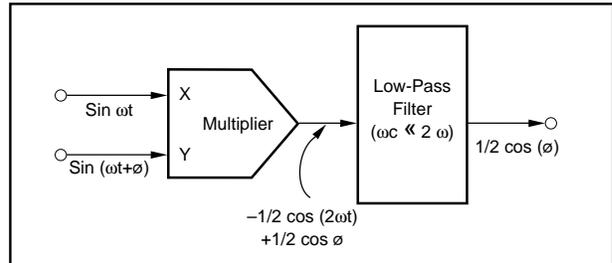


FIGURE 4. The Multiplier Chip Works In A Phase Detector. When two signals of equal frequency are multiplied, the operation produces a DC component proportional to the cosine of the angle between them.

## COMPARING DOUBLE-BALANCED MIXERS

Specification	Typical Double-Balanced Diode Mixer	Multiplier Chip	
		DC to 0.5MHz	0.5 to 10MHz
Carrier Feedthrough	25dB	60dB	40dB
Isolation: RF Input to Local Oscillator	40dB	60dB	40dB
Local Oscillator to Mixer	30dB	60dB	40dB
RF Input to Mixer	25dB	60dB	35dB
Third-Order Intermodulation Intercept	1Vrms	50Vrms	2Vrms
Frequency Range	Several kHz to several GHz <sup>(1)</sup>	DC to 10MHz	DC to 10MHz

NOTE: (1) The frequency range for any one mixer is usually about three decades.

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## STRIKE UP THE BANDWIDTH

The limited bandwidth of transconductance multipliers is customarily attributed to the output amplifier. Though the bandwidth of the MPY634 multiplier chip can be kept to 50MHz by the core transistors, the output amplifier slashes that figure to 1MHz. The drop is caused by interaction between the core's output resistance and the large Miller capacitance at the amplifier's input, creating a pole at about 1MHz.

Designers have usually compensated for that interaction by making the output amplifier's -3dB cutoff frequency occur at or before the pole. However, the new chip shifts out that pole in frequency, so that the gain can be sustained far beyond 1MHz. Keeping the gain constant, however, mandates an unchanging ratio of transconductances in the output and input amplifier stages. To keep the ratio constant over a wide band, the input stage's transconductance,  $G_{m_{IN}}$ , must decrease at the same rate that the output transconductance,  $G_{m_{OUT}}$ , does for increasing frequency.

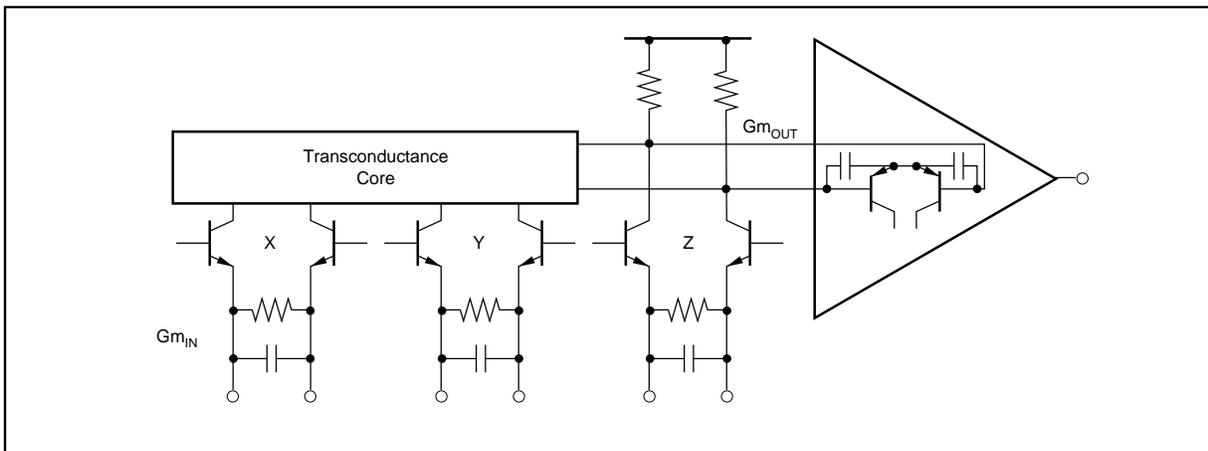
The gain of each input amplifier is the ratio of its load impedance to the transconductance of the input amplifier stage (see the figure). Also, the overall transconductance of the output stage is the output resistance of the core plus the input capacitance and transconductance of the output am-

plifier. This lumped value looks like a direct load to voltage-to-current converter Z and to the core. Since the core is transparent to converters X and Y, they see  $G_{m_{OUT}}$  as the direct load. Moreover, because  $G_{m_{OUT}}$  represents the load impedance for all the converters, the wideband gain is  $G_{m_{OUT}}/G_{m_{IN}}$ .

For  $G_{m_{IN}}/G_{m_{IN}}$  to remain constant over a broad frequency range, the RC time constants of both transconductances must be within 100% of each other. Fortunately, with worst-case process and temperature variations, the match between the RC time constants can be held to within 20%.

In this multiplier chip, a reactive element of the input stage keeps the transconductance ratio constant. The element, a small nitride capacitor, parallels the normally high resistance  $G_{m_{IN}}$ . In fact, this purely resistive transconductance causes  $G_{m_{OUT}}$  to limit the bandwidth in the first place.

The resistive portions comprise thin-film resistors that can be matched to within 1%. The capacitive portion of  $G_{m_{OUT}}$  depends mainly on the quiescent current of the output amplifier's differential inputs. That current is laser-trimmed to a known value. Consequently, only the absolute tolerance of the added nitride capacitor determines the match between the capacitive portions of  $G_{m_{OUT}}$  and  $G_{m_{IN}}$ .



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