THE GYRATOR - an IC inductor

Until the fairly recent development of this simulated inductor, the inherent bulk of even the smallest inductor has excluded inductance from all microelectronics except hybrid LSI's.

by STEVE LECKERTS

THERE IS A SEALED CONTAINER, THE MYTHical black box, sitting in front of us with two terminals coming out of the top. Our problem is to nondestructively determine what electrical component is inside. When we connect a constant-amplitude current source to the terminals and varying the frequency we find that as the frequency increases the voltage across the terminals decreases with a mathematical pattern. The voltage decreases exactly inversely with frequency. To complete the characterization we compare the phases of the input and output currents and see that the phase of the voltage lags the current by 90° irrespective of frequency. Our observations can be summed up by the mathematical expression $Z_1 = V_1/I_1 = 1/2\pi jfK$ where K is a positive constant and j is a mathematical ruse to show the 90° phase shift. If K is replaced by a C the expression is the same as the impedance of a capacitor of value C and we identify the hidden component as a capacitor.

Now take a second black box with two sets of terminals and connect the output terminals to those of the first box. The second box contains an active transistor circuit. It does not hold any energy-storing components, specifically capacitors and inductors. The box transforms the output current to input voltage and the output voltage to input current. Looking into the input terminals we expect to see the response of the first box with the roles of voltage and current interchanged. We repeat our measurements and find that now the voltage increases directly with frequency. Also the phase relationship has reversed with the voltage now leading the current by 90°. The expression for this measurement is written

$Z_2 = Vin2/Iin2 = 2\pi jfC$,

where C is the value of the capacitor in the first black box. Well this new two-box hookup behaves exactly like an inductor. The only thing unusual about the expression is that in place of the L that would normally be found is the value of the real capacitor C.

Note that we end up with $Z_2 = 1/Z_1$ which is not too surprising since impedance is the ratio of voltage to current and we have reversed them. By interchanging the roles of current and voltage we have simulated an inductor. This second black box is a gyrator, so called because it is electrically analagous to the mechanical gyroscope.

The gyrator

Fig. 1 shows the basic form of the gyrator with two transconductance amplifiers in a negative feedback loop. The amplifiers have both high input and output impedances. For a voltage input of v_{in} amplifier 1 has a current output i_1 equal to $g_m v_1$. We use the familiar transconductance notation gm since it is the ratio of current to voltage. Likewise the output of amplifier 2, i_{in} is $g_m v_2$.

This amplifier has a negative sign in front of its current gain indicating a phase reversal or 180° phase shift through it. If we load the output of amplifier 1 with a capacitor we have a situation where the input current i_{in} is transformed into the capacitor voltage v_2 and the input voltage v_1 is transformed into the capacitor current i_2. As we have explained this is precisely what we want and will result in an indictive looking input impedance. For those of you who would like to indulge in some algebra follow the next few equations:

$i_{in} = g_m v_2 = g_m v_c$

$i_{out} = -g_m v_{in} = i_c$ or $v_{in} = -i_c/g_m$

now $i_c = v_c/Z_c = v_c/(\frac{1}{2}\pi jfC) = -2\pi jf v_c$

and the input impedance $Z_{in} = v_{in}/i_{in} = \frac{-i_c/g_m}{g_m v_c} = \frac{2\pi jfC v_c/g_m}{g_m v_c} = \frac{2\pi jfC}{g_m^2}$

The input impedance therefore looks like an inductor with a simulated inductance equal to C/g_m^2. We have assumed the gm of both amplifiers to be identical in magnitude. If they are not the expression would be $C/g_{m1}g_{m2}$.

A circuit proposed[1] to realize this basic gyrator configuration on an IC is drawn in Fig. 2. Each transconductance amplifier has two FET's and two bipolar transistors. High input impedance and circuit Q is assured by the input p-channel junction FET and the high output impedance results since the output is at the junction of a FET drain and bipolar collector. The circuit shown in Fig. 3 is interesting[2] because it is balanced using two differential amplifiers. One amplifier uses npn's and the other pnp's making the biasing easy, using direct connections between the corresponding output collectors and input bases.

This circuit is particularly convenient since it simulates a floating inductance completely unrestrained by a ground connection. If desired, either one of the input terminals can be grounded.

Next, Fig. 4 is an extremely simple circuit[3] that uses an RC combination and a single FET to simulate inductance. The FET corresponds directly to amplifier 1 in the original scheme of Fig. 1. Instead of the second amplifier a pseudo-current source is created using a large resistor R. Of course this is an approximation to a higher impedance active current source and we must expect a compromise in the Q of the resulting

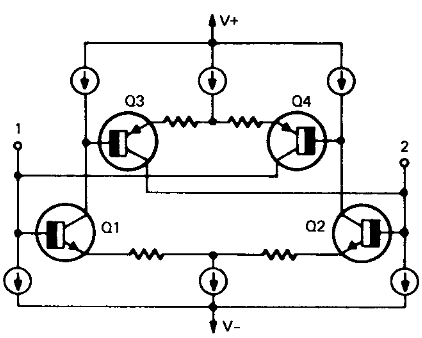

FIG. 3—BALANCED GYRATOR floating inductor.

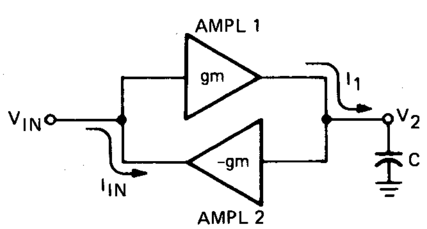

FIG. 1—BASIC GYRATOR uses two transconductance amplifiers as shown.

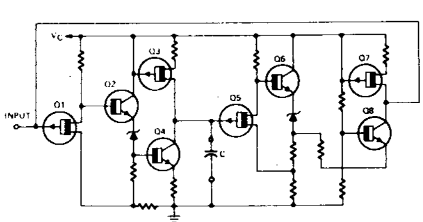

FIG. 2—IC GYRATOR CIRCUIT has p-channel junction FET's for high Q.

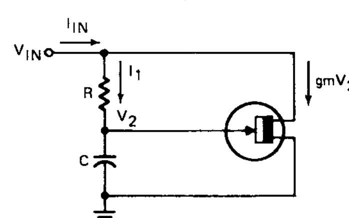

FIG. 4—SIMPLE GYRATOR uses high resistance to approximate transconductance amplifier.

inductance. In Fig. 5 transconductance amplifiers[4] are constructed by combining voltage and current amplifiers. The gain blocks are either a positive or negative unity gain current amplifier driven by unity gain voltage amplifiers. The current and voltage amplifiers are interconnected with a series resistor which sets the transconductance equal to the inverse of the resistor. Presenting an essentially zero input resistance, the

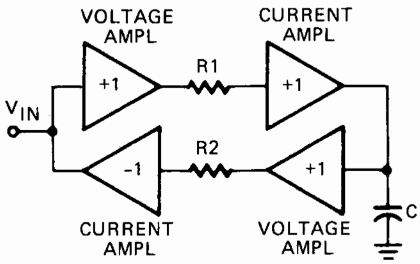

FIG. 5—GYRATOR WITH UNITY GAIN. Voltage and current amplifiers combined to form transconductance amplifiers.

current amplifier conducts equal input and output currents. These two currents are then equal to the input voltage divided by the resistance.

Other impedance converters

A Japanese manufacturer has recently announced an integrated circuit which is different from the pure gyrators we have been describing. Not only does its input impedance look inductive but it also generates a negative resistance component. Positive feedback in the manner of a Q multiplier must be added to the negative feedback used for impedance transformation. Mitsumi says the small chip it has named Semicon L is a replacement for the large coils used in radio and TV receivers.

Figure 6 is the schematic for the device which is further simplified by replacing Q2

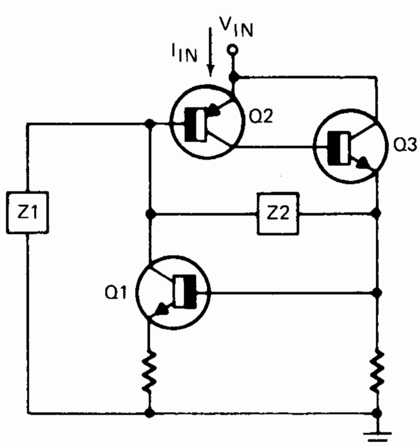

FIG. 6—MITSUMI'S SEMICON L impedance converter is diffused onto a small monolythic integrated circuit.

and Q3 with a single pnp transistor. The composite configuration of Q2 and Q3 is commonly used by IC manufacturers to compensate for the low beta of the lateral pnp's they can produce compatable with their normal npn processing. The collector current of Q2 feeds Q3's base producing a beta roughly equal to the product of the two individual device betas. Q3's collector returned to Q2's emitter completes a negative feedback path lowering the impedance at this composite emitter terminal. The emitter of Q3 acts as the collector of the composite device; Q2's base as the base, and the emitter-base junction as the emitter.

While the simplified schematic of Fig. 7

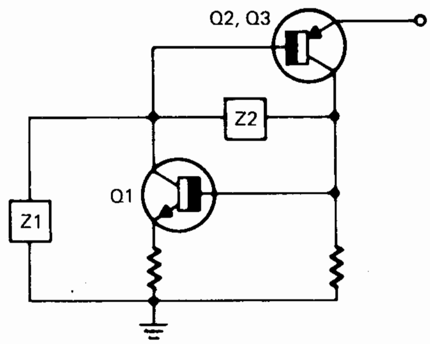

FIG. 7—SIMPLIFICATION OF FIG. 6 by redrawing composite Q2, Q3 configuration as single equivalent device.

appears elementary, it is actually quite difficult to analyze and very careful assumptions must be made to produce meaningful results.

Each of the two transistors in Fig. 7 has its collector connected to the other device's base. The two 180° base to collector phase shifts add to give 360° or 0° around the loop, which is positive feedback. The input impedance is of the form $Z_{in} = -AZ_1 + B/Z_2$ where A and B are real positive numbers. Z_1 is a resistor and Z_2 a capacitor giving an input impedance that is a negative resistance in series with an inductance. Inductance values in the range of 1 MH to 5H with Q's between 50 and 100 are claimed with frequency capability to 15 MHz.

Besides synthesizing inductors with gyrators, complete filter designs can be based around them. Figure 8 is the design of such a low pass filter. It is a fifth-degree Chebyschev type[5] with a 0.2 dB in band ripple and a cutoff frequency of 3.4 kHz. Fig. 9 is the schematic of a gyrator suggested by the proponent of this filter technique. Q1, Q2 and Q5, Q6 are Darlington connected amplifiers for high input impedance by virtue of the multiplication of the device betas. Q4 and Q8 are constant-current sources which combine with Q3 and Q7 respectively to form high impedance current outputs. The constant-current source enables current to flow into or out of the gyrator terminals

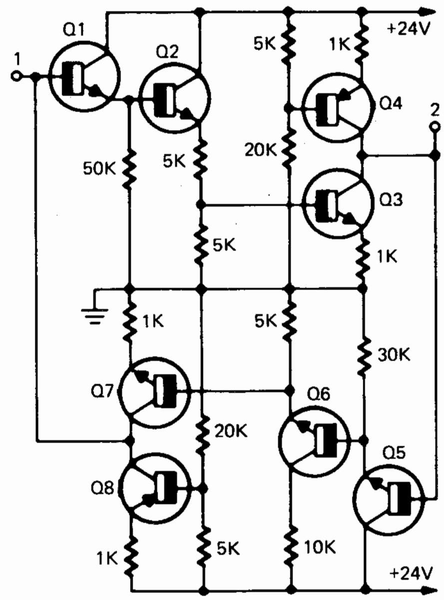

FIG. 9—GYRATOR WITH BIDIRECTIONAL current output.

which is necessary to charge or discharge circuit capacitances. When Q3 is cutoff current will flow out of terminal 2 from constant current source Q4. When Q3 conducts a current equal to that flowing in Q4 there will be a net zero output current from terminal 2. If Q3 conducts a larger current than can be supplied by Q4 there must be a net current flow into the terminal.

Some engineers say that making a negative impedance converter to synthesize negative capacitors is easier than building a stable usable gyrator. Not only are we concerned with the synthesis of inductance or inductive circuitry but important secondary criteria must be carefully examined. Whenever transistor circuitry replaces passive devices additional noise sources are injected. The added noise has to be kept at a minimum so the product performance is not degraded. Dynamic range is another key specification. Active circuitry has finite signal excursions that can be handled before overloading takes place, generally at a level considerably lower than could be handled by the physical counterpart. Temperature stability is also a vital consideration. In the final analysis the secondary characteristics are what makes one design superior to another.

Fig. 10 shows how a negative capacitance can be generated using a differential amplifier. The negative capacitance seen at the terminals is of value $2/fC_1R_3$. The design of a 104 to 108 kHz telephone channel bandpass filter[6] using negative capacitance is given in Fig. 11.

We have demonstrated how inductive networks can be simulated with resistors and capacitors combined with feedback amplifiers. With careful use of integrated cir-

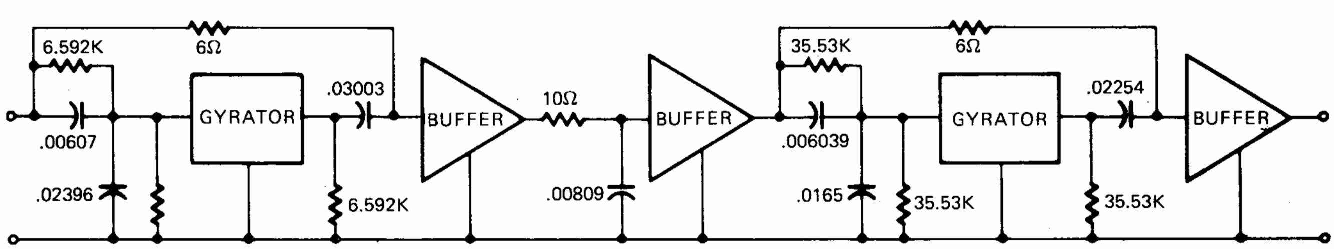

FIG. 8—FIFTH DEGREE CHEBYSCHEV lowpass gyrator filter.

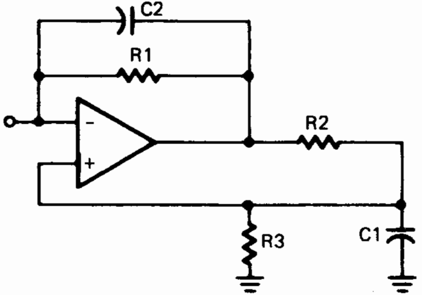

FIG. 10—NEGATIVE IMPEDANCE CONVERTER looks like negative capacitor.

cuits and thick film techniques practical circuits can be put together. Products designed using gyrators and negative impedance converters (NIC's) may soon appear in our homes. As we found with the tunnel diode any one technique is not a panacea but another tool to be added to our stockpile. The gyrator simulated inductor will eventually replace those components where space is at a premium or where there will be a savings in cost either by a physical reduction in parts count or by easing circuit adjustment using computer controlled laser or abrasive trimming. **R-E**

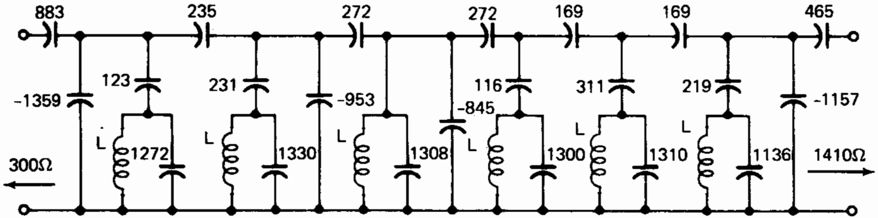

FIG. 11—TELEPHONE CHANNEL bandpass filter L=1.523 mH. Capacitors in pF.

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