Basic MODAMP MMIC Circuit Techniques

Application Note S001

Introduction and MODAMP MMIC Structure

Agilent Technologies' MSA (Monolithic Silicon Amplifier) series MODAMP silicon bipolar Monolithic Microwave Integrated Circuits (MMICs) are intended for use as general purpose 50 ohm gain blocks.

Their single chip construction minimizes size and parasitics and maximizes uniformity; these factors translate into low cost and excellent high frequency performance. The wafer fabrication process uses nitride self-alignment for precise registration, ion implantation for precise doping control, and both gold metalization and nitride passivation for high reliability. A variety of geometries are available, allowing the designer to select for appropriate gain, power, noise, and frequency chacteristics. Packaging options, ranging from inexpensive plastics to high reliability, hermetically sealed ceramic microstrip, provide a choice of cost, reliability, and electrical performance characteristics.

The internal structure of the MODAMP MMIC is a Darlington connected pair of transistors with resistive feedback and a simple resistive biasing scheme. A general schematic is shown in Figure 1. Since S_{11} and S_{22} are set primarily by resistive divider networks, they remain relatively constant over a wide frequency range. The use of both series feedback (R_E adjusting the emitter voltage of Q2) and shunt

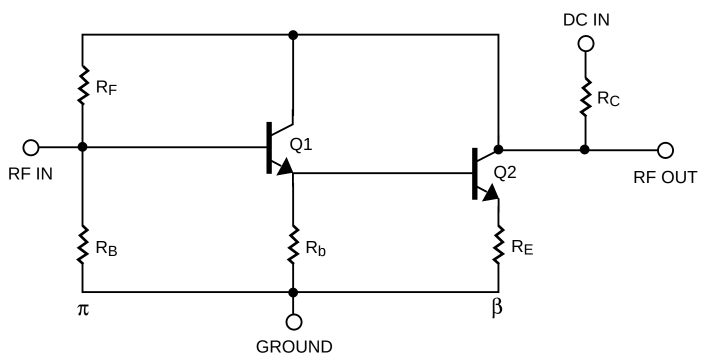

Figure 1. General MODAMP Schematic

feedback (R_F adjusting the base voltage of Q1) helps desensitize the design to variations in active device parameters. A “bleeder” resistor attached to the emitter of Q1 decouples the quiescent bias point of Q1 from the β of Q2 (without this resistor the emitter current of Q1 would necessarily equal the base current of Q2). R_C also serves a feedback function. As the transistors draw more current, the voltage drop across R_C will decrease the collector voltages, tending to shut down the transistors. Since device β (and, therefore, collector current, given a fixed bias) tends to increase with temperature, R_C also serves as a temperature compensating element.

Since the internal resistive networks prematch both input and output to 50 ohms, MODAMP MMICs are particularly easy to design with. To design an amplifier, all that’s needed is a 50 ohm microstrip line, blocking capacitors, and some very simple bias circuitry. Nonetheless, because MODAMP MMICs are high frequency devices, there are some basic construction rules that should be followed when using them.

Stripline Structures

Figure 2 shows a typical microstrip structure. Line impedances are determined by strip width (w), board dielectric material (ε_r), and dielectric thickness (h). Since the impedances of the MODAMP MMICs are prematched to operate in a 50 ohm system, microstrip lines should be as close to 50 ohms as possible to realize full specified performance. Dimensions of 50 ohm line for some common board materials are shown in Table 1. Operation in systems with characteristic impedances other than 50 ohms is possible with somewhat reduced performance; in particular most MODAMP MMICs perform satisfactorily in 75 ohm systems without additional impedance matching.

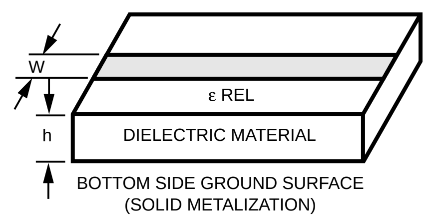

Figure 2. Microstrip Structure

Board Material Selection

A board material should be selected that is appropriate for the intended frequency of operation. Although G10 (epoxy-glass board) is an acceptable low cost choice for small signal, low frequency applications, inconsistencies in the dielectric (usually glass pockets) can cause problems at frequencies above 500 MHz, or with low impedance power stages built on the same board. PTFE woven-glass has much more consistent dielectric characteristics, and performs well to frequencies in excess of 2 GHz. It is also a fairly rugged material that can tolerate substantial rework, and is not particularly sensitive to heat or humidity.

Table 1. Line widths for 50 ohm line for various board materials

Board Material	ε	Thickness	w/h for 50 Ω	w for 50 Ω
RT/Duroid 5870[1]	2.3	0.015"	2.90	0.044"
PTFE-Woven Glass	2.55	0.010"	2.55	0.025"
Fiber (Typ.)		0.031"	2.55	0.079"
		0.062"	2.55	0.158"
Epoxy-Glass (G10)	4.8	0.062"	1.75	0.108"
Alumina/E10[2]	10.0	0.025"	0.95	0.024"
		0.050"	0.95	0.048"

Notes:
1. Trademark of Rogers Corp. for its PTFE non-woven glass PC material, (RT is reinforced teflon and PTFE is polytetraflourethylene).
2. E-10 and Epsilam-10 are trademarks of 3M for its ceramic filled PTFE substrate.

Table 2. Representative board material and thickness for various package options.

Package	04	20	35	70	85
Lead Width	0.030"	0.030"	0.020"	0.040"	0.020"
Representative	G10	PTFE	PTFE	5870	G10 or PTFE
Board	(0.062")	(0.031")	(0.010")	(0.015")	(.062") (.010")

Duroid is the favored material of many microwave designers because of its high dielectric consistency and low dielectric dissipation. Note that 50 ohm line on 0.015" RT/duroid-5870 is a particularly good match to the lead width of the 70 mil package, meaning minimal step discontinuity effects with this combination. RT/duroid is a somewhat fragile material – it crushes fairly easily, and glues do not adhere well to its substrate so thin metalization patterns are subject to lifting if abused with repeated rework. Some versions can also be quite hydroscopic, and can show substantial dielectric shifts with variations in humidity. Care should be taken when working with this material.

Alumina is an excellent high frequency material, but because it is a ceramic, it is expensive to process and requires etchants or a diamond scribe for line rework. It is the material of preference for hybrid circuits. Several manufacturers make soft board materials with dielectrics closely approximating those of alumina. These boards are also good choices for high frequency (> 1 GHz) applications.

All boards must be plated on both sides. For soft boards, 1 oz. Cu plating is the most common choice. When etching the circuit pattern, the entire bottom side plating should be left intact to provide the best possible ground plane.

Parasitics

During board layout, care should be taken to minimize all parasitics. Remember that extra lead length equals extra inductance added to the design. This is particularly important if the circuit is to be operated above 1 GHz. Transmission lines should, whenever possible, run flush to the package. For some package options this will require that a hole be made in the circuit board so that the MODAMP MMICs' leads are in the same plane as the transmission line. MODAMP MMICs should be mounted on the etched side of the board to minimize the inductance of "fed through" connections. Abrupt changes in transmission line width also create parasitic effects, called step discontinuities. Although the complete model for such a discontinuity can become quite complicated, the overall effect of the step from a MODAMP MMIC lead to a 50 ohm transmission line is typically 0.05 to 0.2 nH of extra series inductance. Tapering the transmission lines from 50 ohms down to the MODAMP MMIC lead width helps minimize this effect. Bends in transmission lines also create parasitic effects and should be avoided when possible; when they must be used, the corners should be chamfered to prevent the bends from acting as extra shunt capacitance. For more information on the properties of microstrip structures, see K.C. Gupta, et al, *Microstrip Lines and Slotlines*, Artech House, 1979, Dedham, MA.

To illustrate how important parasitic effects can be, a "careful" design using a MSA-0204 on 1/16" PTFE woven-glass was simulated using a computer program and analyzed from 500 MHz to 3 GHz. Both step discontinuities and parasitic inductances were included in the model. The blocking capacitor was assumed to be a 100 pF, 0.1 inch square ceramic chip with infinite Q and an associated parasitic inductance of 0.9 nH. The analysis was of the input circuit mismatch only; assuming losses due to output mismatch are of a similar magnitude, the total amplifier loss would be about double that shown. To help distinguish the effects of parasitic mismatch from those due to device impedances, the simulation was also made of both the network with parasitics terminated in a "perfect" (50 + j0 ohm) device and of a MSA-0204 operated in an ideal (parasitic-less) system. Table 3 shows the results of the analysis. In this case, amplifier gain loss ranges from negligible (less than 0.1 dB) at 500 MHz to nearly 0.4 dB at 3 GHz. Remember that the results shown are for minimal realistic parasitics. If the layout is "sloppy," impedance mismatches in excess of 2:1 and consequent amplifier gain decreases of 1 dB or more can be expected.

Table 3. Parasitic effects on input impedance mismatch of MSA-0204.

Frequency (MHz)	MSA-0204, No Parasitics		Parasitics Only		MSA-0204 + Parasitics	
	VSWR	Loss, dB	VSWR	Loss, dB	VSWR	Loss, dB
500	1.09:1	0.0	1.01:1	0.0	1.18:1	.03
1000	1.23:1	.04	1.12:1	.01	1.39:1	.11
1500	1.29:1	.07	1.22:1	.04	1.46:1	.15
2000	1.29:1	.07	1.30:1	.07	1.45:1	.15
2500	1.26:1	.05	1.38:1	.11	1.45:1	.15
3000	1.26:1	.05	1.45:1	.15	1.53:1	.19

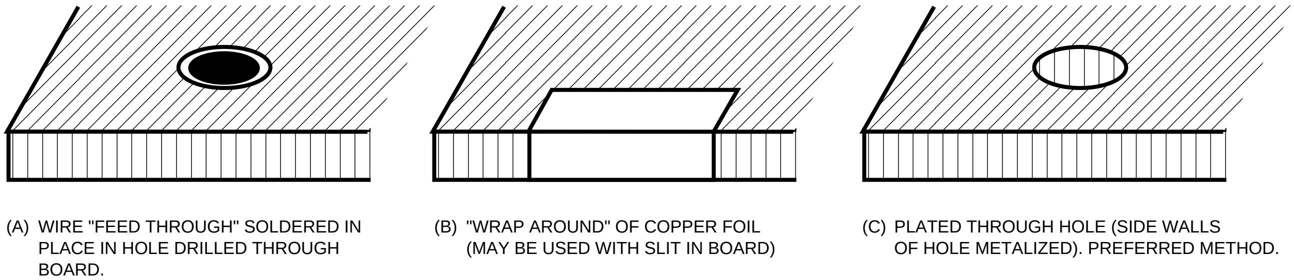

Figure 3. Methods of Realizing Minimal Length Return Paths to Ground

Grounding

Perhaps the second most important consideration in PC board layout (after impedance matching) is good RF grounding. Ground planes should be kept as large and as solid as possible. Return paths for high frequency circulating currents must be kept as short as possible, especially at the “emitters” of the MODAMP MMICs. If, for example, plated through holes are used as ground returns, they should be placed directly under the ground leads of the MODAMP MMIC and be located as near as possible to the body of the package. This is because any additional path length here acts as series inductance, which translates into unwanted emitter resistance at operating frequencies. Gain, power compression, and high frequency rolloff will all be degraded if proper grounding techniques are not used. Figure 3 shows a variety of ways of providing good return paths between topside ground connections and the bottom ground plane.

Figure 4 shows the effects of parasitic emitter inductance resulting from poor RF grounding. The device analyzed is the MSA-0135. Gain vs. frequency curves are shown for emitter inductances ranging from 0 to 4 nH.

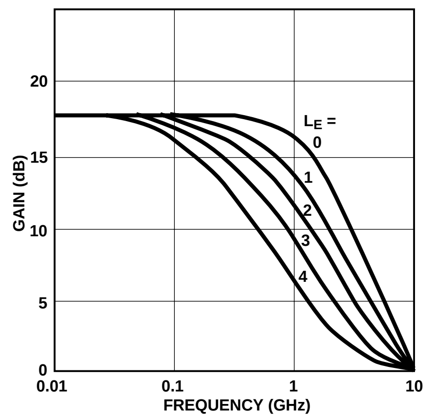

Figure 4. Gain vs. Frequency as a function of emitter inductance (L_E) for the MSA-0135

DC Blocking Capacitance

DC blocking capacitors must be used in both the RF input and the RF output lines to isolate the resistive bias circuitry of the MODAMP MMIC from the source and load resistances. These capacitors will also put limits on the frequency response of the finished amplifier. Low frequency response will be determined by the capacitor’s value; it must be high enough to be a reasonable RF “short” at the lowest frequency of operation. High frequency response will be limited to the frequency at which the capacitor’s associated parasitic inductance becomes resonant with the blocking capacitor ($1/ [2 \pi \ \sqrt{LC}$] Hz, where L = parasitic inductance in Henrys, and C = the capacitor value in Farads). Operation above this frequency often leads to highly unpredictable circuit behavior.

Figure 5 shows typical effects of blocking capacitors on impedance match as a function of frequency, capacitance, and parasitic inductance. Note that low frequency match is determined by capacitor value, with the parasitic inductance having negligible influence; whereas at higher frequencies, the value of the parasitic inductor dominates the match, with the value of the capacitor becoming unimportant so long as it is large enough to be a low series impedance path. The ratio of capacitive reactance to parasitic resistance is called the Q of the capacitor. Blocking capacitors with high Qs should always be used to minimize insertion losses.

Biasing

In order to deliver full performance, MODAMP MMICs must be biased correctly. The internal resistive networks determine individual transistor operating points; all the user needs to do is present the proper voltage at the DC input terminal. For the purpose of bias stability over temperature, the internal transistors should have their bias supplied through a collector resistor (labeled R_C in Fig. 1). This resistor works in two ways. First, it compensates for increases in device β with temperature by dropping the transistor's collector voltages whenever they try to draw more collector current. Coupled with this effect is the fact that the collector resistor will itself be changing in value over temperature.

Resistors with positive temperature coefficients such as the common carbon composite (+0.0001% per degree C) do an excellent job of compensating for the temperature drift of the negative coefficient on-chip resistors.

For bias stabilization over a temperature range of -10° to + 100°C, a drop of at least 1.5 volts across the collector resistor is necessary. The larger this voltage drop is, the more stable the bias will be. An interesting point is that for a fixed bias (constant quiescent current vs. temperature), the gain of the MODAMP MMIC will decrease as temperature increases. A voltage drop of about 2 V across the collector resistor allows the bias swing over temperature to compensate for this gain change, yielding best gain flatness over temperature.

Table 4 shows an example of how selection of the bias stabilization resistor influences performance over temperature. These results come from device simulations using PSPICE and correlate well with observed performance of actual amplifiers. Note that with no stabilization resistor the user risks having the MODAMP MMIC self-destruct at elevated temperatures. In general, bias current will increase as temperature increases (due to increases in device betas with temperature); gain may either increase or decrease depending on how well the bias shift compensates for the decreased gain at a constant bias at higher temperatures.

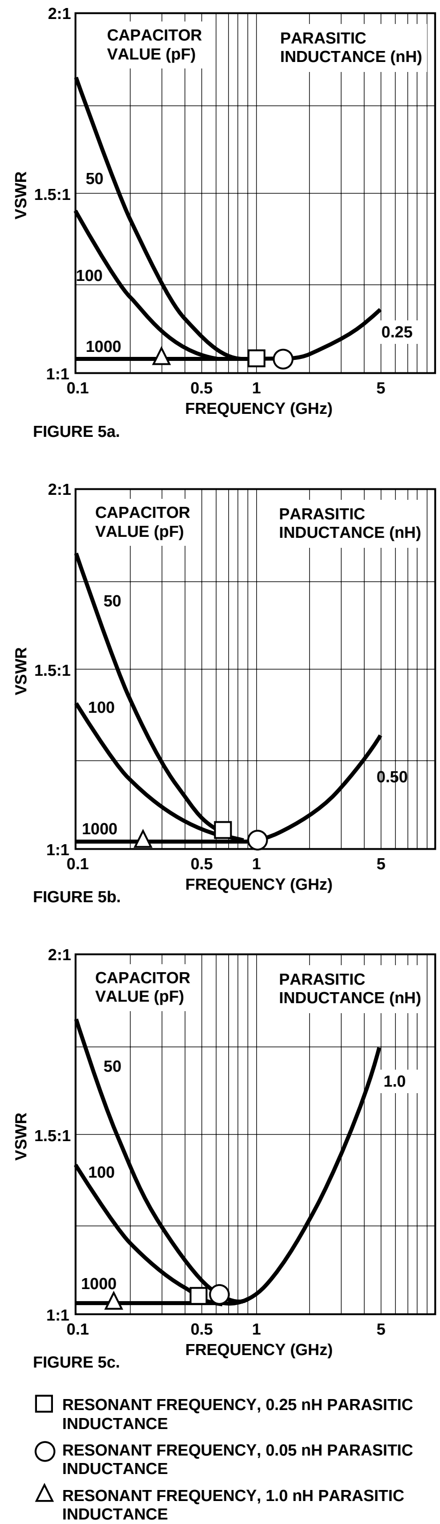

Figure 5. Effects of DC blocking capacitors on VSWR as a function of frequency, capacitance and parasitic inductance

Table 4. Effects of R_C on performance over temperature.

MSA-0104   Operating Voltage = 5.07 V Nom.

Voltage Drop, volts	Resistor Value, ohms	Temperature, degrees C	Bias Current, mA	Power Gain @ 100 MHz, dB
0	0	-10	9.5	-0.5
		25	18.4	18.8
		100	**	**
1.5	82	-10	14.2	17.0
		25	17.3	18.3
		100	24.1	19.0
2.0	100	-10	16.3	18.5
		25	18.9	18.9
		100	24.6	19.0
7.0	412	-10	16.1	18.3
		25	16.8	18.1
		100	18.3	17.5

** Device destroyed due to excessive current draw.

The value of the bias stabilization resistor R_C is given by:

$$R_C = \frac{V_{CC} - V_d}{I_d} \text{ OHMS}$$

where V_{CC} = the power supply voltage applied to R_C (in volts)
V_d = the voltage at the DC input terminal of the MMIC (in volts)
I_d = the quiescent bias current drawn by the MMIC (in amps)

The recommended values of I_d and V_d can be found on the individual MODAMP MMIC data sheets, both in the *Electrical Specifications* table and above the listing of S-parameters.

The dissipation of this resistor is given by:

$$P_{diss} = I_d^2 \times R_C \text{ watts}$$

The power rating of R_C must exceed Pdiss; if necessary, resistors with lower power ratings may be paralleled to achieve the necessary dissipation capability. Some MODAMP MMICs are available with the collector resistor on the chip. This has obvious size and parts count advantages. The tradeoff is for high frequency performance (see the discussion of grounding above) and bias flexibility (only one supply voltage will be appropriate for a given internal resistor value). Also, the on-chip resistors have negative temperature coefficients, and will not hold the MODAMP MMIC's bias as constant over temperature as will an external carbon resistor.

Chokes and Bypass Capacitors

It is recommended that an RF choke (large value inductor) be used in series with the bias stabilization resistor. Although the choke is not generally needed to keep the RF out of the DC (the relatively high impedance of the bias stabilization resistor compared to a 50 ohm load is sufficient for this), it is needed to keep the stabilization resistor from appearing in parallel with the load circuit, and thus degrading the output match. A good rule of thumb is that the impedance of the choke at the lowest frequency of operation (given by $2 \pi \cdot F \cdot L$) plus the value of the stabilization resistor should be at least 500 ohms. A 10 µH inductor works well as a choke at frequencies as low as 10 MHz; it can be either a molded inductor (for low cost applications) or a chip inductor (in cases where space is at a premium). At lower frequencies several turns of wire on a high permeability ferrite bead should be used. If the choke is omitted, the designer should expect a gain loss of between 0.5 and 1 dB and a decrease in P_{1dB} of as much as 2 dB from the guaranteed performance due to load impedance mismatch.

A large value bypass capacitor (1 µF or so) should be used in conjunction with the choke to present a low impedance path to ground for any signal that does manage to get past the choke. This capacitor should be attached between the supply side of the RF choke and ground.

Typical Circuit Layouts

Figure 6 shows a typical MODAMP MMIC circuit board layout that uses the above construction techniques. The layout is for 1/32" PTFE woven-glass board – a reasonable compromise between cost, durability, and electrical performance. Note that the transmission lines have no bends and are tapered near the package of the MODAMP MMIC to minimize step discontinuities. Twelve plated through holes, including two under the emitter leads, provide solid ground planes and minimal emitter parasitics for best high frequency performance. The gaps in the transmission line are appropriate for 50 mil ceramic chip capacitors, which have relatively low associated parasitic inductances – typically about 0.5 nH. The DC pad arrangement requires that a bias stabilization resistor be used, but makes the use of an RF choke optional. If the choke is not used, the stabilization resistor would be connected between the output 50 ohm line and the V_{supply} line, and the bypass capacitor would be attached between the V_{CC} line and ground. Spacing is appropriate for 1/4 watt carbon resistors, molded inductors, and 1 µF electrolytic capacitors. The layout has been designed so that the section between the arrows in Figure 6 can be repeated for multiple cascaded stages. Overall circuit dimensions are 1" x 1.5" for a single stage, with each additional stage adding 1" to the overall length. The size was chosen for convenience of assembly; a more compact layout providing a three stage cascade of MODAMP MMICs in the same space and using chip resistors and inductors is shown in Figure 7.

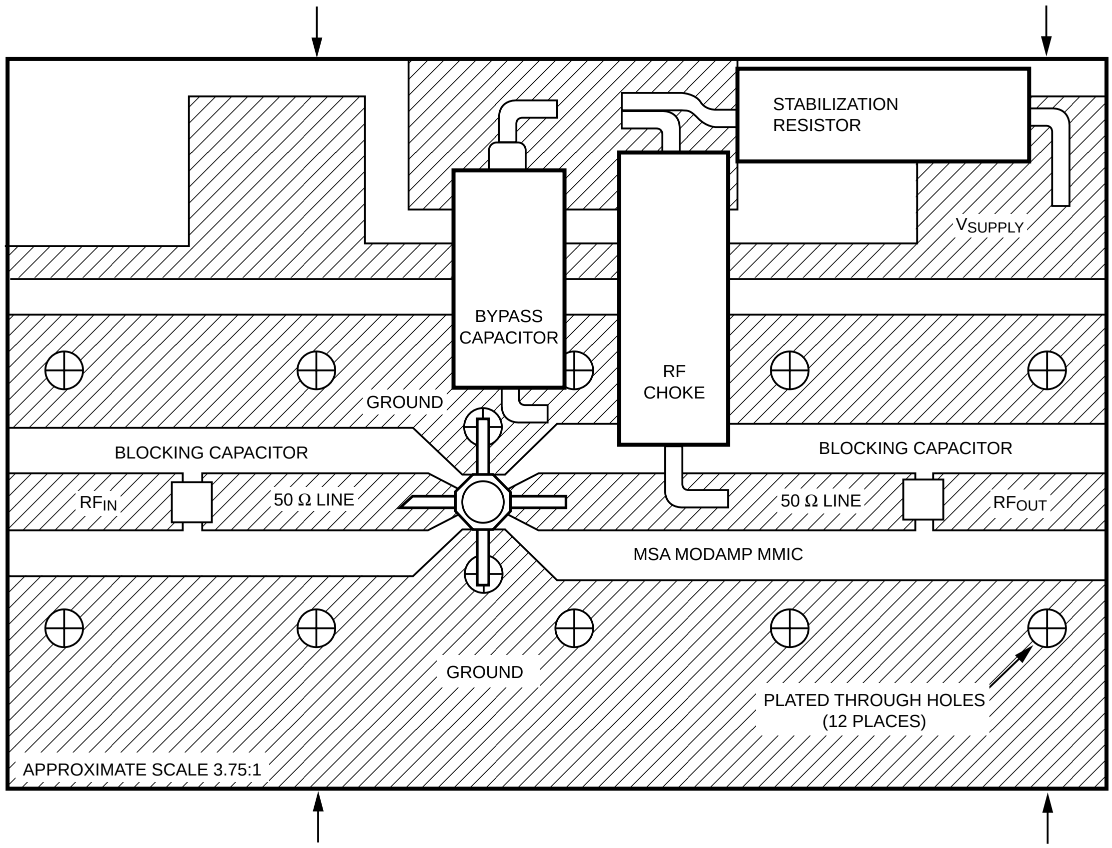

Figure 6. Typical MODAMP MMIC Circuit (dual ground configuration)

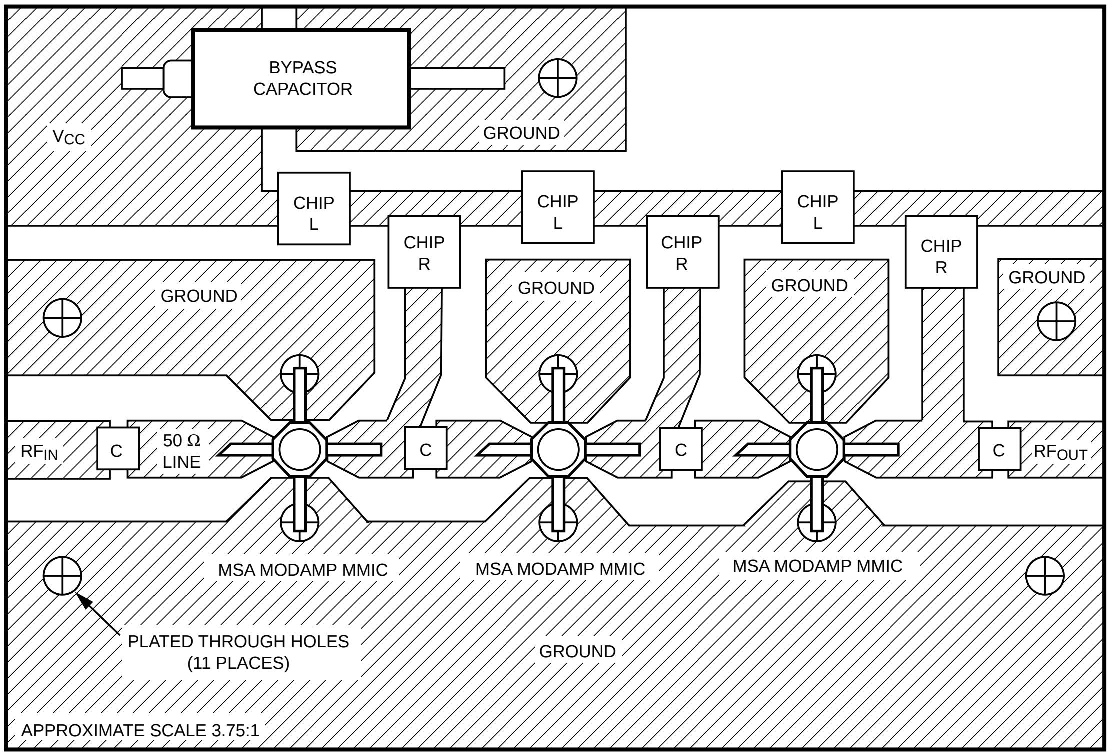

Figure 7. MODAMP MMIC Circuit Layout (three stage cascade)

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