HEWLETT® PACKARD

A Low Distortion PIN Diode Switch Using Surface Mount Devices

Application Note 1049

Abstract
One of the practical applications of the surface mounted PIN diode is in the design of low current, low cost RF switches. In the design of such circuits, the diode is generally treated as a current controlled ideal resistor which is switched between low resistance and high resistance states.

However, the PIN diode has some important second order non-linear characteristics which can give rise to the generation of harmonic and intermodulation distortion in switching circuits, particularly those which employ high RF power. A low distortion SPDT switch, using a new type of PIN diode designed specifically for low distortion performance, is described.

Introduction
All circuits which contain non-linear elements such as diodes and transistors produce certain kinds of distortion to various degrees. The three types of distortion which are most often of concern are as follows:

Harmonic Distortion:
This is a single-tone distortion product, resulting when a voltage at a single frequency f, applied to a non-linear device, creates spurious voltages at frequencies 2f, 3f, ..., Nf. Of most concern, because they are the closest to the desired signal, are the second and third harmonics. The order of the distortion product is given by the frequency multiplier; for example, the second harmonic is a second order product.

Intermodulation Distortion:
This is a multi-tone distortion product. It results when two or more signals, of equal or unequal amplitude, mix in a non-linear device to produce unwanted signals whose frequencies are related to those of the original input voltages. In certain industries, the number of input signals may exceed 10, and analysis becomes very complex. To keep matters as simple as possible, many semiconductor manufacturers make two-tone measurements using two voltages which are equal in amplitude and closely spaced in frequency. Given two such input signals at frequencies f_1 and f_2, one can compute several significant intermodulation distortion products from the equation

$$Mf_1 \pm Nf_2$$

where $M, N = 1, 2, 3, \ldots$

The order of the distortion product is given by the sum $M + N$.

Of the infinite number of distortion products described by this equation, one is of special significance. The third order products given in Table 1 are important because they exist on either side of the original signals f_1 and f_2 and cannot be removed by filtering.

HARMONIC DISTORTION:
GIVEN AN INPUT AT FREQUENCY f
SECOND HARMONIC AT 2f
THIRD HARMONIC AT 3f

INTERMODULATION DISTORTION:
GIVEN TWO EQUAL AMPLITUDE INPUTS AT FREQUENCIES f_1 AND f_2
THIRD ORDER AT $2f_1 - f_2$
THIRD ORDER AT $2f_2 - f_1$

Table 1. Important Distortion Products.

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Cross Modulation Distortion: This is another form of multi-tone distortion. The non-linear device causes modulation on one signal of frequency f_1 to be transferred to a second signal or carrier of frequency f_2. Cross modulation distortion will not be treated in this paper. However, it is worth noting that Lepoff[1] has shown that the intercept point for this distortion product is generally 2.5 dB below that for third order harmonics.

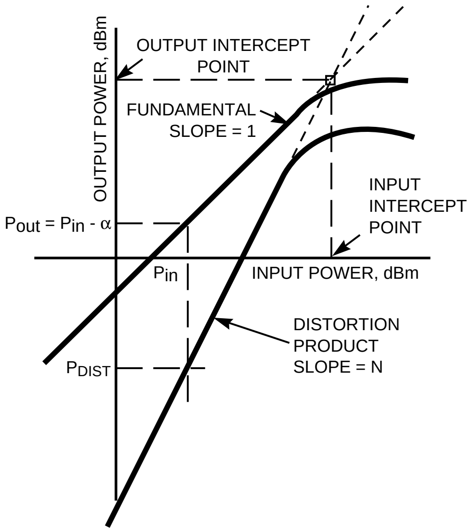
The behavior of all three types of distortion products is shown in Figure 1. As can be seen, an increase of 1 dBm in the applied signal's power will result in a 2 dBm increase in the second order products and a 3 dBm increase in the third order products. Since the level of measured distortion is dependent upon the level of the input signal, it is convenient to specify distortion in terms of a fictitious constant, the intercept point. In making distortion measurements, it is most convenient to measure the input power of the signal(s) applied to the DUT (Device Under Test) and the output power of the distortion products. For this reason, and because the input intercept point varies less with attenuation, the input intercept point is the one most often calculated and specified. However, in the case of the PIN diode switch, insertion loss (α) is typically less than 1 dB, so the input and output intercept points are essentially equal. For the balance of this paper, reference will therefore simply be made to the intercept point, and the simplified equations shown in the box in Figure 1 will be used.

The primary source of distortion in PIN diode switches is conductivity modulation of the charge within the I layer of the diode under forward bias and capacitance modulation of the diode under reverse bias. Distortion can be controlled by the proper choice of diode characteristics and by the design of the switch circuit itself.

PIN Diode Considerations

In their seminal treatment of distortion in PIN diodes, Caverly and Hiller[2,3,4] discuss the origins of distortion and the effects of various device parameters upon distortion performance. In summary, their work shows that:

- For a given forward biased diode and frequency, series PIN diodes produce more distortion than shunt diode switches and attenuators.
- For a given forward biased diode and circuit topology, distortion improves (decreases) as the frequency of the im-pressed signal(s) increases.
- In reverse biased PIN diodes, distortion gets worse with increase in frequency and improves with increase in diode I layer thickness.



α = ATTENUATION
IP_{in} = INPUT INTERCEPT POINT, dBm
IP_{out} = OUTPUT INTERCEPT POINT, dBm

DISTORTION PRODUCT	SLOPE = N
2nd HARMONIC	2
3rd HARMONIC	3
2nd ORDER IM	2
3rd ORDER IM	3

GENERAL EQUATIONS FOR INTERCEPT POINT

$$IP_{out} = \frac{NP_{out} - P_{dist}}{N - 1}$$

$$IP_{in} = \frac{N(P_{in} - \alpha) - P_{dist}}{N - 1} + \alpha$$

FOR THE CASE OF $\alpha \le 1$ dB,
2nd ORDER $IP_{in} = 2P_{in} - P_{dist}$
3rd ORDER $IP_{in} = \frac{3P_{in} - P_{dist}}{2}$

Figure 1. Behavior of Distortion Products.

1 Jack Lepoff, "A New PIN Diode For UHF-VHF Applications," Proceedings of the National Electronics Conference, Vol. XXVI, pp 434 - 439, Dec. 7 - 9, 1970.

2 Robert Caverly and Gerald Hiller, "Distortion in PIN Diode Control Circuits," IEEE Trans. MTT, vol. MTT-35, No. 5, pp 492 - 500, May 1987.

3 Robert Caverly, "A Nonlinear PIN Diode Model For Use in Multi-Diode Microwave and RF Communication Circuit Simulation," Proceedings of the International Symposium on Circuits and Systems, pp 2295 - 2299, August 1988.

4 Robert Caverly and Gerald Hiller, "Distortion in Microwave and RF Switches by Reverse Biased PIN Diodes," IEEE MTT-S Digest, pp 1073 - 1076, May 1989.

- In forward biased PIN diode switches, the intercept point for distortion is proportional to the square of the diode's carrier lifetime divided by I layer thickness.
- The second order intermodulation distortion products will be 6 dB higher than that of the second harmonic.
- The third order intermodulation distortion products will be 9.5 dB higher than that of the third harmonic.

The equations which predict distortion intercept points are shown in Table 2.

To illustrate the use of these equations in the prediction of a given diode's distortion performance, four surface mount PIN diodes were analyzed and tested as listed in Table 3. They ranged in I layer thickness from 5.5 µ to 130 µ and nominal lifetime varied from 60 ns to 3 µs. The first two were designed for low cost, low current switching applications, the third is a general purpose diode of an older design and the fourth is a new product targeted specifically for low distortion switching applications. Since certain applications, such as battery powered portable radios, are limited in the amount of current which is available, each diode was tested at two or three current levels. The highest current for each nearly saturated the diode; at that current the I layer resistance was close to its minimum. At least one lower current was chosen such that the insertion loss of the diode, when operated as a series switch, would be well under 1 dB. It is worth noting that the lifetime of a PIN diode varies slightly over this range of currents.

The first diode, HSMP-3820, has twice the capacitance (0.6 pF) of the other three (0.3 pF); because it is not directly comparable in frequency performance, its evaluation will be saved for the next section.

The three 0.3 pF diodes were each mounted in series in a 50 Ω microstrip line, and biased with external bias tees. Insertion loss under forward bias and isolation under reverse bias was recorded. Using the equipment illustrated in Figure 2, harmonic distortion was measured at two forward currents and three frequencies for each. It is worth commenting that, at certain frequencies with some diodes, the distortion products were more than 100 dB below the input signal; good filters are essential to accurate measurements of this type. The data were converted to intercept points which are plotted in Figure 3.

The measured intercept points show good agreement with those predicted by the equations of Figure 3. Certainly, those performance indicators summarized at the beginning of this section are borne out in the data. Distortion performance improves with frequency, with diode lifetime, with I layer thickness and with forward

IM_2 = 2 - TONE 2nd ORDER INTERMODULATION DISTORTION INTERCEPT POINT

$$= 34 + 20 \text{ LOG } \frac{fQ}{R_S} \text{ dB}$$

IP_2 = 2nd HARMONIC INTERCEPT POINT

$$= IM_2 + 6 \text{ dB}$$

IM_3 = 2 - TONE 3rd ORDER INTERMODULATION DISTORTION INTERCEPT POINT

$$= 24 + 15 \text{ LOG } \frac{fQ}{R_S} \text{ dB}$$

$$= \frac{3}{4} IP_2 - 1.5 \text{ dB}$$

IP_3 = 3rd HARMONIC INTERCEPT POINT

$$= IM_3 + 9.5 \text{ dB}$$

WHERE

f = FREQUENCY, MHz

$$= \frac{f_1 + f_2}{2} \text{ FOR TWO-TONE MEASUREMENTS}$$

$Q = I\tau$

I = DIODE FORWARD CURRENT, mA

τ = DIODE LIFETIME AT A GIVEN CURRENT, µSEC

R_S = DIODE RESISTANCE AT A GIVEN CURRENT, Ω

Table 2. Equations For Intercept Points For a Single Diode, from Caverly and Hiller.

DIODE	W(µ)	I (mA)	R_S (Ω)	τ (ns)
HSMP-3820	5 1/2	5.0	0.55	60
		1.0	1.3	65
		0.2	5.0	75
HSMP-3890	6 1/2	10.0	1.5	170
		0.5	5.3	200
HSMP-3830	22 1/2	40.0	1.1	250
		4.0	4.4	300
HSMP-3880	130	40.0	1.2	3000
		7.5	3.5	3600

WHERE τ = LIFETIME, W = I-LAYER THICKNESS

Table 3. PIN Diode Evaluation.

current. For example, the lifetimes of the tested samples of HSMP-3830 and HSMP-3890 were nearly the same. However, the I layer thickness of the former is more than 3 times that of the latter, resulting in substantially improved distortion performance. When the HSMP-3880 is used with 40 mA of bias at frequencies above 100 MHz, the second harmonic intercept point is above 1 GW (10^9 W), indicating very low distortion produced at normal operating power levels. In the section which follows, it will be seen that this intercept point can be easily increased by another 15 dBm.

In order to obtain the second harmonic data described above, distortion levels as low as -130 dBc had to be measured. The equations of Table 2 predict third harmonic and two-tone third order distortion products as low as -180 to -200 dBc at 300 MHz, levels beyond the capability of the equipment used. For this reason, third order products were measured only at 123 MHz, and are shown in Table 4. Even at this lower frequency, these products were difficult to measure at saturation currents. Nevertheless, good agreement is seen between predicted intercepts and those which could be measured.

When using the equations of Table 2 to predict the distortion performance of a forward biased diode, one must know its resistance and lifetime at the current one plans to use. Resistance information is generally found in PIN diode data sheets, and it can easily be verified by measuring the insertion loss of a forward biased series diode and computing the value of Rs which corresponds to that loss. The measurement of lifetime is somewhat more complicated, and lifetime varies from lot to lot of a given diode. However, typical lifetime data are available

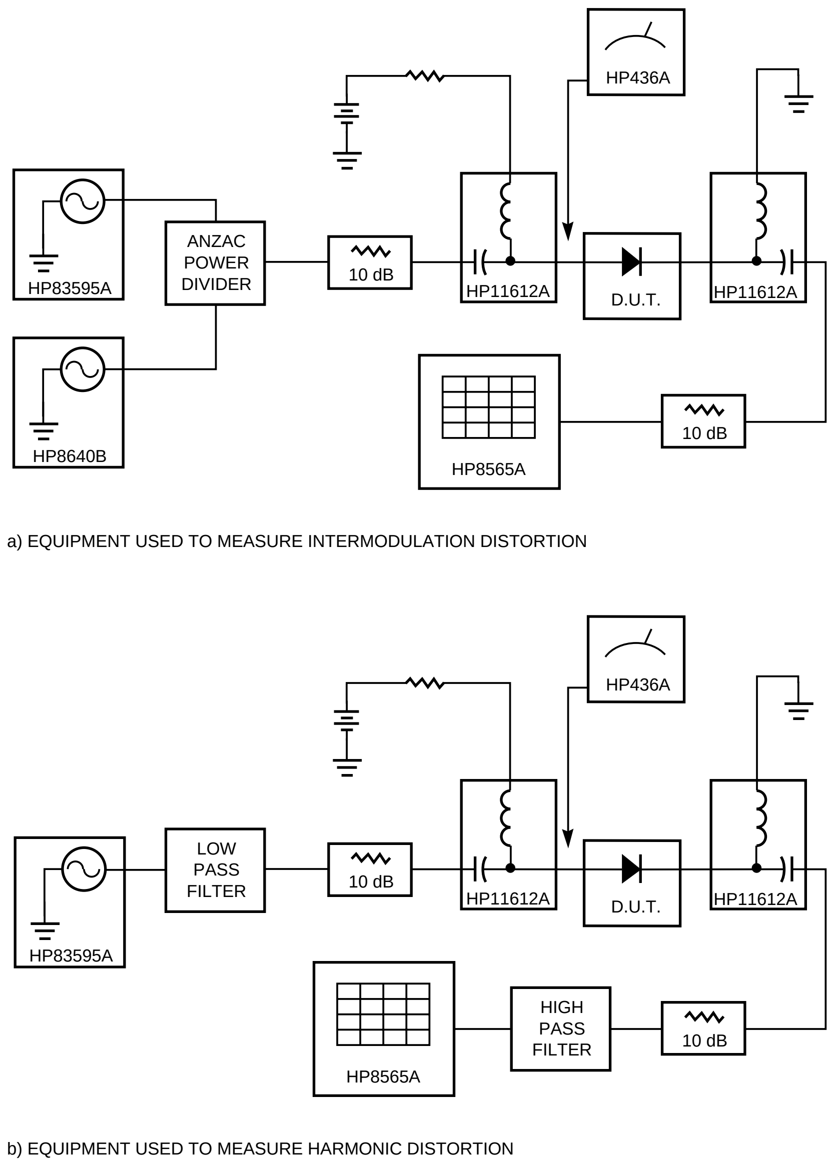


Figure 2. Measuring Equipment.

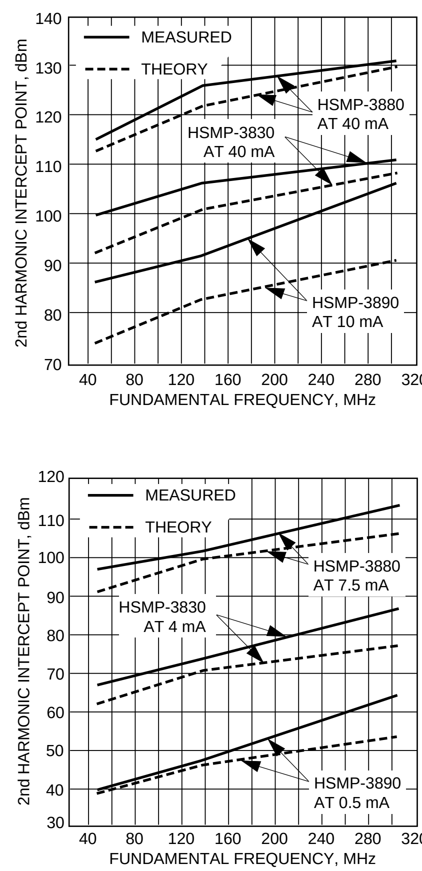


Figure 3. Distortion in Forward Biased PIN Diodes

from diode manufacturers, and quite good accuracy can be obtained if one uses 120% of that value at the reduced current which results in an R_S of 4 Ω.

In a SPDT switch designed as described in the section below, the diodes in the "ON" arm are forward biased, with distortion performance as described above. However, the diodes in the "OFF" arm are reverse biased. A thorough discussion of the distortion characteristics of reverse biased diodes is beyond the scope of this note. However, at these frequencies and with the diodes evaluated, distortion products under reverse bias were less significant than those produced in forward bias.

Circuit Considerations

In the practical application of SOT-23 packaged PIN diodes, the very large inductance of that package (≈ 2 nH) makes it difficult to obtain good levels of isolation from a shunt diode at frequencies much above 150 MHz. This inductance is much less troublesome in the case of the series diode switch, where diode and package capacitance are important in the maintenance of good isolation. For this reason, this paper will focus on the application of surface mounted PIN diodes as series switching elements.

In the previous section, PIN diode characteristics were treated without regard to circuit considerations. However, a review of Figure 4 will show how certain distortion products can be reduced by means of a circuit "trick."

Figure 4 provides a simplified equivalent circuit for a single series PIN diode as well as two different arrangements of two series diodes. The single diode can be represented by a resistor R_S in series with a voltage generator v(t). This voltage, resulting from the excitation of the diode by input current i(t), consists of an infinite series containing all of the unwanted distortion products. When two identical diodes, with the same value of R_S, are placed in series in the same orientation, the two coherent voltage generators combine their outputs in-phase, resulting in a lowering of the distortion intercept points (an increase in distortion). For N identical diodes in series, Caverly[3] gives the equations for second and third order intermodulation distortion intercept points as:

IP_2 = Second order IMD intercept point, dBm

$$= K_1 \frac{N^2 A}{(1 - \sqrt{A})^4}$$

IP_3 = Third order IMD intercept point, dBm

$$= K_2 \frac{N^2 A}{(1 - \sqrt{A})^3}$$

where N = number of identical diodes in series, and

$$A = \frac{2Z_O}{2Z_O + NR_S}, \text{ and}$$

K_1, K_2 = factors independent of the number of diodes.

For values of R_S less than 4 Ω, these equations predict that two in-phase series diodes will have a second order IMD intercept point ≈6 dB lower, and a third order IMD intercept point ≈ 3 dB lower, than that for a single diode of the same type and biased with the same current.

DIODE TYPE: HSMP-3890

IF mA	RES. OHMS	τ nsec	CALC 2nd	MSRD 2nd	CALC 3rd	MSRD 3rd	CALC IM3	MSRD IM3
10	1.00	170	83	86	66	>60	56	–
1	3.70	190	54	63	44	45	35	38
0.5	5.30	200	47	48	39	33	29	34

DIODE TYPE: HSMP-3830

IF mA	RES. OHMS	τ nsec	CALC 2nd	MSRD 2nd	CALC 3rd	MSRD 3rd	CALC IM3	MSRD IM3
40	1.10	250	101	107	79	>58	70	–
4	4.40	300	71	74	56	51	47	–

DIODE TYPE: HSMP-3880

IF mA	RES. OHMS	τ nsec	CALC 2nd	MSRD 2nd	CALC 3rd	MSRD 3rd	CALC IM3	MSRD IM3
40	1.20	3000	122	126	95	>65	85	–
7.5	3.50	3600	100	102	78	>65	69	–

2nd = SECOND HARMONIC DISTORTION
3rd = THIRD HARMONIC DISTORTION
IM3 = TWO-TONE THIRD ORDER INTERMODULATION DISTORTION

Table 4. One and Two Tone Distortion Intercept Points, Measured At 123 MHz.

However, when two PIN diodes are placed anti-series, the equivalent circuit (shown at the bottom of Figure 4) predicts that even order (2nd, 4th, etc.) distortion products will cancel out to the extent that the two diodes are matched in their characteristics.

To experimentally verify the theory outlined above, three circuits were built using the HSMP-3820 PIN diode. This device was chosen because its thin I layer and short lifetime result in relative high (and easily measured) levels of distortion. The first circuit consisted of a single series diode, as shown schematically at the top of Figure 4. The second consisted of two diodes in series, in-phase. The third consisted of two diodes in anti-series configuration, with a wideband choke (Coilcraft 1008CS-561 560 nH surface mount inductor) providing bias to the center. All three circuits used wideband external bias tees at input and output. Measured data are compared to predicted for second harmonics, third harmonics and two-tone third order intermodulation distortion at three different currents. In general, there is good correspondence between forecast and observed intercepts, except for second harmonics in the anti-series pair. In this specific case, illustrated by the plot at the bottom of Figure 5, the improvement over the in-phase pair is typically 20 dBm, with a 15 dBm increase in intercept point when compared to the single diode.

Thus, it can be seen that the use of an anti-series pair of PIN diodes as a switching element can lead to very low levels of even-order distortion products, even when a high distortion diode is chosen for the task.

In the case of all four types of diodes, it was found that the theory of Caverly and Hiller for forward biased series diode switches was reasonably accurate in the prediction of intercept points.

SPDT Switch

The concept of anti-series PIN diodes as a switching element was incorporated into a wideband SPDT switch, as shown schematically in Figure 6. All components are of the surface mount type. Hewlett-Packard HSMP-3880 PIN diodes were chosen because of their extremely low distortion. Each PIN diode has a capacitance (at negative bias) of less than 0.3 pF, resulting in a total capacitance in each arm under 0.15 pF. This sets the upper limit on the useful frequency range of the switch at something well over 1 GHz. 560 nH Coilcraft chokes were chosen because their self resonance frequency is well over 1 GHz, yet they have sufficient inductance to permit the switch to be used at frequencies as low as 50 MHz. The large capacitance of the Kyocera capacitors provides good bypassing over this entire frequency range.

The switch was realized on 0.032" thick FR-4 microstrip as shown in

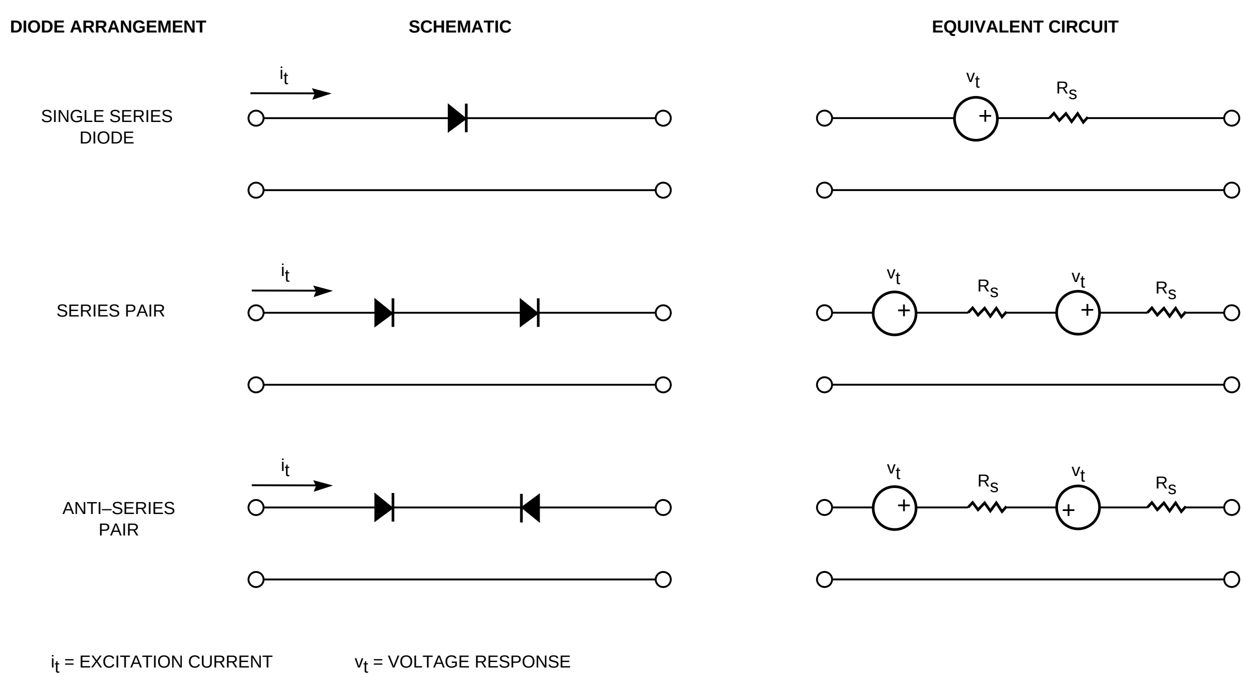


Figure 4.

ONE AND TWO TONE DISTORTION INTERCEPT POINTS, MEASURED AT 123 MHz

SINGLE HSMP-3820 DIODE

IF mA	RES. OHMS	TAU nsec	CALC 2nd	MSRD 2nd	CALC 3rd	MSRD 3rd	CALC IM3	MSRD IM3
5	0.55	60	77	87	61	61	51	–
1	1.30	65	56	59	45	41	36	34
0.2	5.00	75	31	23	27	22	18	23

SERIES PAIR, HSMP-3820 DIODE

IF mA	RES. OHMS	TAU nsec	CALC 2nd	MSRD 2nd	CALC 3rd	MSRD 3rd	CALC IM3	MSRD IM3
5	0.55	60	71	81	58	60	48	–
1	1.30	65	50	55	42	40	33	34
0.2	5.00	75	25	24	24	22	15	24

ANTI-SERIES PAIR, HSMP-3820 DIODE

IF mA	RES. OHMS	TAU nsec	CALC 2nd	MSRD 2nd	CALC 3rd	MSRD 3rd	CALC IM3	MSRD IM3
10	0.55	60	–	103	58	60	48	–
2	1.30	65	–	77	42	41	33	32
0.4	5.00	75	–	41	24	19	15	24

2nd = SECOND HARMONIC DISTORTION
3rd = THIRD HARMONIC DISTORTION
IM3 = TWO-TONE THIRD ORDER INTERMODULATION DISTORTION

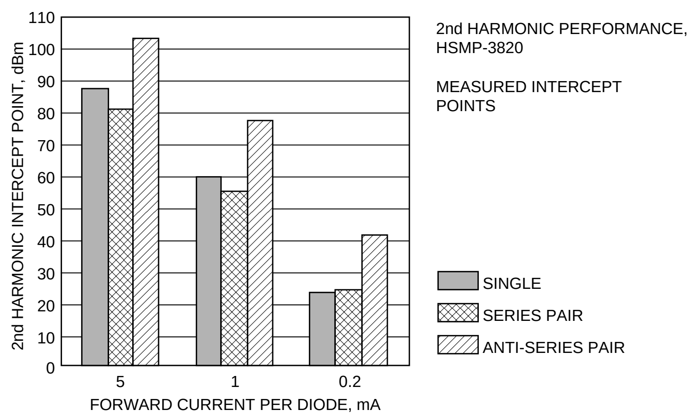
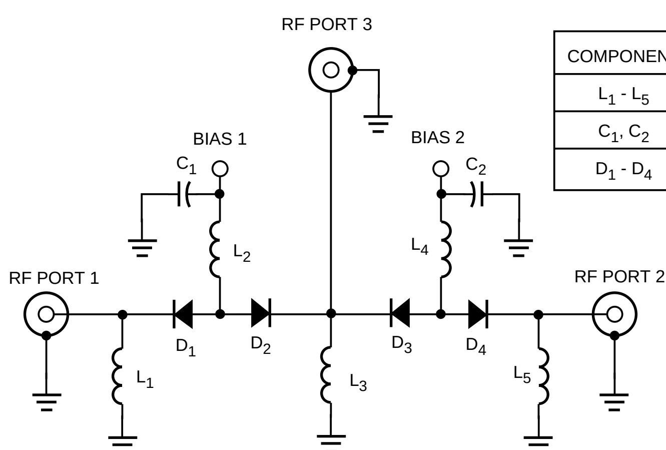


Figure 5.



COMPONENT	VALUE	MFG/PART NUMBER
L_1 - L_5	560 nH	COILCRAFT 1008CS-561
C_1, C_2	47,000 pF	KYOCERA 0805Z473M2P03
D_1 - D_4	–	HEWLETT-PACKARD HSMP-3880

Figure 6.

Figure 7. Note that, in order to provide reasonable distance between components for ease of assembly, the diodes are spaced about 0.27" apart. This separation, amounting to 15° at 1000 MHz, provides an additional 7 dB of isolation at that frequency. Three via holes provide ground on the upper surface of the board.

Swept frequency measurements of the switch are shown in Figures 8 and 9. Insertion loss in the "ON" arm is under 1 dB from 50 to 1000 MHz with 80 mA of bias applied to the two diodes. Using 15 mA of bias results in an increase in insertion loss to 1.3 dB. Return loss over the band was 10 dB minimum, with a typical value of 20 dB or more. Over this same frequency range, "OFF" arm isolation was 32 dB minimum, 40 dB typical. It is worth noting that these diodes are fully depleted at zero Volts reverse bias; the use of negative bias on the "OFF" arm diodes did not increase isolation. The "hole" in the isolation at 160 MHz is the result of the "OFF"

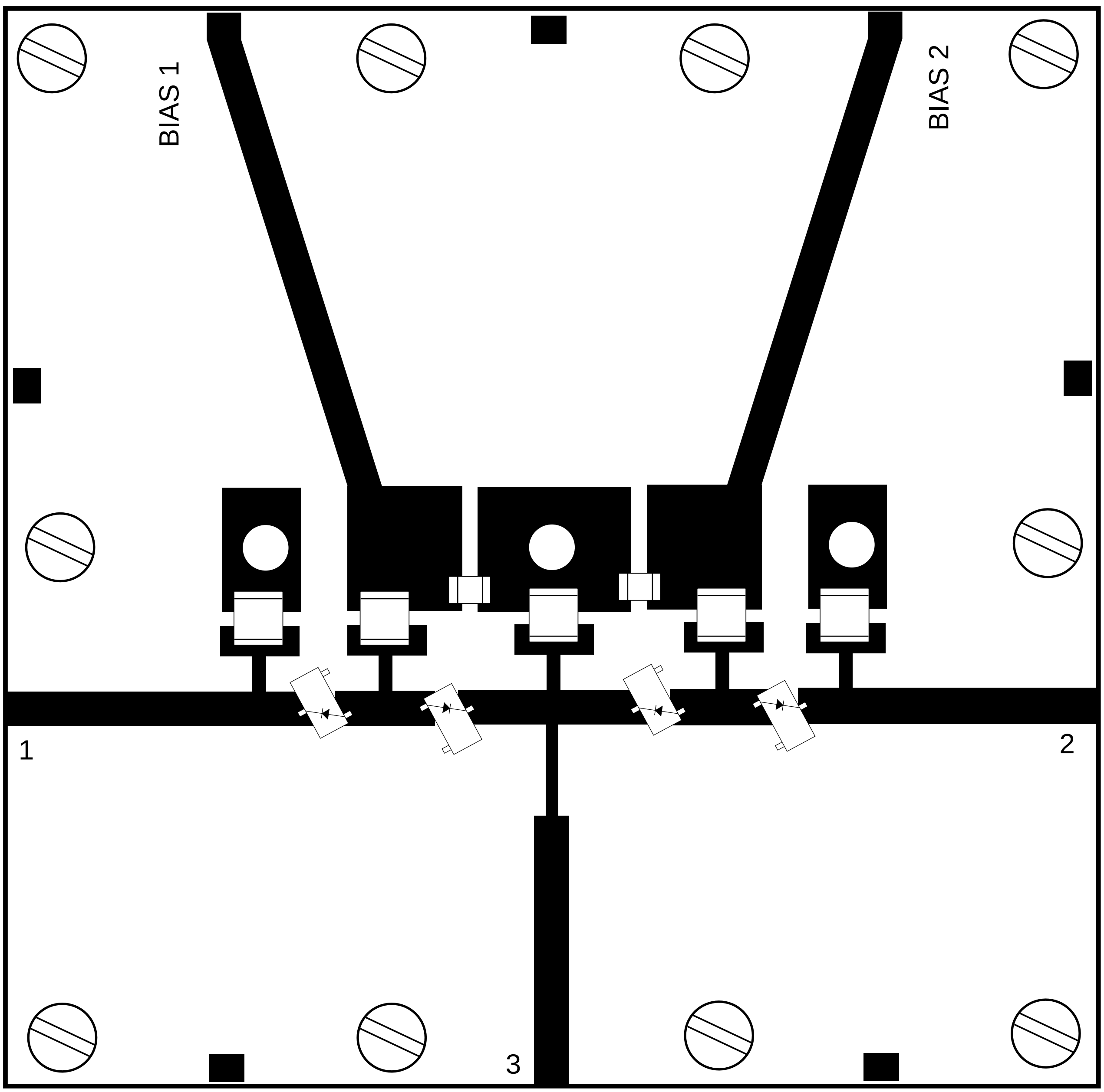


Figure 7.

arm becoming a filter structure consisting of shunt 560 nH inductors and series 0.3 pF capacitors.

Measurements were made of the second harmonic performance of the switch. A +18 dBm signal at 123 MHz was applied at the common junction (port 3) and observations were made of second harmonic power at both the isolated (“OFF”) and connected (“ON”) outputs. Measurements were made using both 15 and 80 mA bias on the “ON” diodes and from zero to -20V on the “OFF” diodes. Results of the worst case (15 mA forward bias) are shown in Figure 10. From this plot, it can be seen that second harmonic distortion is worst at the “ON” arm, and is improved by the addition of negative bias to the “OFF” diodes. This would indicate that some of the distortion measured in the “ON” arm is being produced in the diodes of the “OFF” arm.

Converting these data, and data taken at 80 mA forward bias, to intercept points results in the plot shown in Figure 11. Here it is seen that the use of anti-series low distortion diodes with a large amount (40 mA each) of forward bias can result in second harmonic intercept points as high as 117 dBm (500 MW).

Conclusion

A simple structure, an anti-series pair of PIN diodes, has been shown to substantially reduce even order harmonic distortion products. A wideband (50 - 1000 MHz) low distortion SPDT switch, using inexpensive surface mount devices, has been described. Finally, it has been shown that the theory of Caverly and Hiller can be used to predict distortion performance in forward biased PIN diodes with reasonable accuracy.

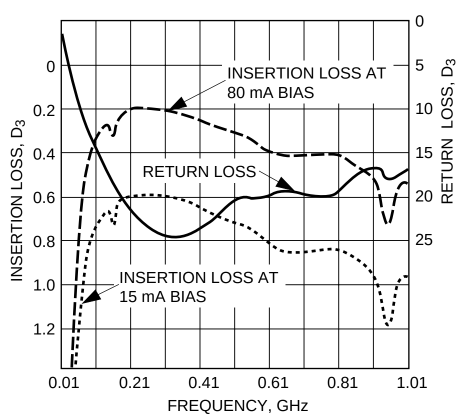


Figure 8. Insertion Loss and Return Loss vs. Frequency

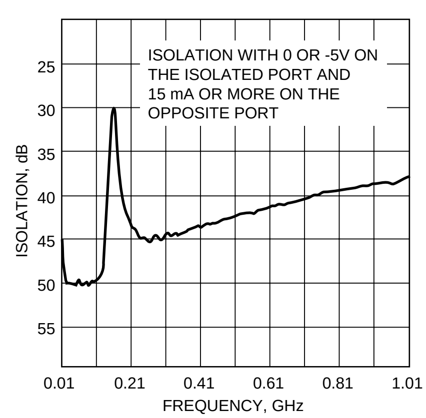


Figure 9. Isolation vs. Frequency

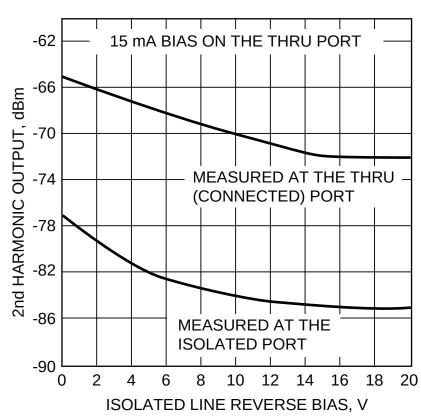


Figure 10. 2nd Harmonics at 123 MHz Input

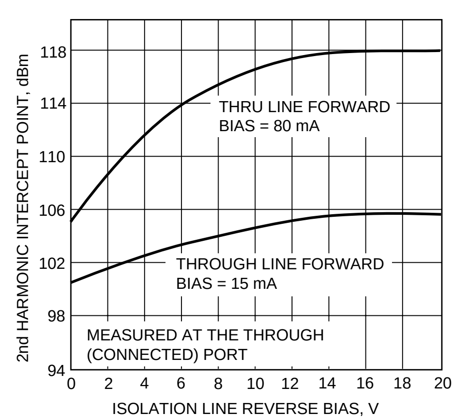


Figure 11. Harmonic Distortion at 123 MHz Input