An Evaluation of Bipolar Transistors Suitable for Active Antenna Applications

by

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Introduction

In the design of active antennas, the intermodulation distortion (IMD) and noise figure (NF) performance of the active devices are important design considerations together with cost and availability. Many designs that have been published in recent years claim to have good IMD performance, but make use of devices that were obsolete even when the circuitry was in the design stage. Other devices that are readily available have improved performance, and it may simply be a matter of the designers lacking sufficient information to make intelligent choices so as to arrive at finished designs having a performance/cost ratio that would be attractive to builders and which make use of devices that are currently in production and which are available from popular distributors such as Digi-Key and Mouser.

What's All This Linearity Stuff, Anyhow?

For HF frequencies and below, the IMD performance of an active antenna or receiver preamplifier is of primary concern as terrestrial and galactic background noise seen by the antenna are primary noise sources, while at the same time congestion, especially in the medium wave (MW) and shortwave (SW) broacast bands (BCB), results in IMD products that interfere with the reception of low-level signals. This is especially true when in close proximity to MW BCB stations which can generate harmonics in a poorly designed active antenna or receiver preamplifier. It is therefore essential that the designer of active antennas at HF frequencies and below gain a thorough understanding of how to select devices on the basis of superior linearity performance.

Performance factors such as breakdown voltages, power dissipation, and NF are typically available in manufacturers datasheets, however IMD performance is rarely available except by observing the characteristics of curve families on a curve tracer or by measuring the performance of the device in a circuit.

When using a curve tracer, there are a number of items that need to be carefully observed in order to ascertain the potential IMD performance of a given device. These include, but are not limited to, the flatness of the individual traces in the linear region, the straightness of the individual traces in the linear region, the spacing between the traces, the saturation voltage, and the transition between the saturation region and the linear region.

Curve families for bipolar devices are generated by applying a fixed base current (I_B) to the device and then varying the collector voltage (V_{CE})while observing the collector current (I_C). For a device that has good linearity characteristics, these individual traces should be fairly close to horizontal and should remain straight between the saturation region and the avalanche (ie - breakdown) region. The terminology for discussing this aspect is the "Early Voltage", and it is described as ther voltage where the individual traces would meet if they were extended into the negative side of the V_{CE} axis. The higher the magnitude of the Early Voltage, the better the potential linearity of the device.

The nature of the saturation region determines the 1dB compression point (P_{1dB}) of the device and has a direct impact on the input and output IMD products, often measured as OIP_3 and IIP_3, being the Third-Order Output Intermodulation Intercept Point and the Third-Order Intermodulation Intercept Point, respectively, though other definitions exist. The saturation voltage at the point where the design load line intersects the vertical collector current (I_C) axis determines the P_{1dB} characteristics of the device, and the smaller this voltage is the higher will be the P_{1dB} performance.

For most devices, the current gain (h_{FE}) will change with the collector current (I_C). This can be seen by way of the spacing between the individual curve traces. The more uniform the spacing between the lines, the better the potential linearity of the device. Generally, h_{FE} will decrease as I_C increases, and the device should be biased away from the point where the variation in h_{FE} becomes noticable.

The portion of the curves that transitions between the saturation region to the linear region plays an important rôle in the linearity of the device. When making OIP_3 measurements, a region in the third-order IMD products is usually encountered where the IMD products rise above the straight 3-to-1 line, and this rise is referred to as "IR (Intermodulation Ratio) Expansion". If the transition from saturation to linear in the curve is sharp, then the IR expansion will be very small. However, the broader this transition zone is the higher the IMD products will rise above the 3-to-1 line.

Certain manufacturers of MMIC devices are overly zealous when representing the OIP_3 performance of their products, typically measuring the IMD products below the region of IR expansion and projecting the OIP_3 point from there, leaving the system designer to find out the hard way that the devices don't perform at all well at higher signal levels. Stanford Microdevices (later Sirenza Microdevices and now part of RF Microdevices) was infamous for this form of specmanship and one simply had to learn to leave them out of consideration.

A Bit of Transistor History

Most of the devices that are found to be suitable for active antennas and receiver front ends have been used extensively in the design of trunkline, multicoupler, and distribution amplifiers for the cable TV (CATV) industry. These amplifiers have very high dynamic range requirements, meaning that they have low NF and high IMD performance, and devices with exceptional linearity together with low NF find immediate popularity. However, they can rapidly become unpopular with designers when less expensive devices having better performance become available, after which they become relegated to second sources such as Central Semiconductor (distributed through Digi-Key) and Advanced Power Devices (part of Microsemi) for the repair of the earlier designs. Familiar low-power devices such as the 2N3866, 2N4427, 2N5108, and 2N5109 have all suffered this fate, as have numerous lesser-known devices such as the MRF581 and the infamous 2N5160.

Small-Signal NPN Devices

A series of five small-signal NPN devices are described here, all of which are currently available from Mouser at very reasonable prices. Fig. 1 displays a series of characteristic curves for each of these devices, while Table 1 lists some of the static characteristics as well as prices and sources for each.

Surprisingly, the venerable 2N2222 can still provide very useful performance at HF frequencies. The characteristic curves shown in Fig. 1A disclose that it has admirable linearity characteristics below 50mA of collector current, after which the saturation and transition regions begin to deteriorate. It is very likely that the 2N2222 will still be around long after cockroaches have become extinct. The 2N2219 is essentially the same as the 2N2222, being the same die but in the larger TO-39 package which can dissipate more heat (800mW vs. 500mW) and which is more convenient in applications where a heat sink is desired.

Both the 2N3904 and the 2N4123 show significant deterioration of the saturation and transition region for collector currents above 25mA, though the 2N3904 retains very good charactristics in the linear region. The 2N4401 has very good linearity characteristics throughout the range of tested collector current, and it

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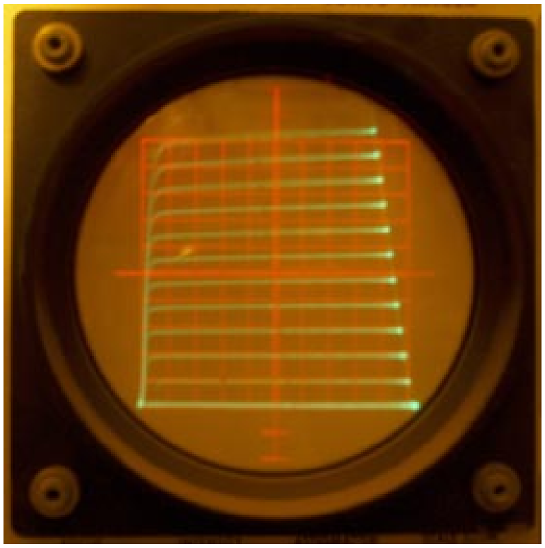

Fig. 1A - 2N2222

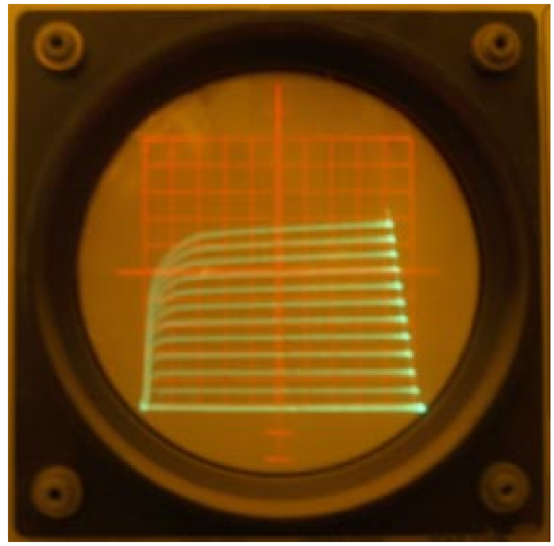

Fig. 1B - 2N3904

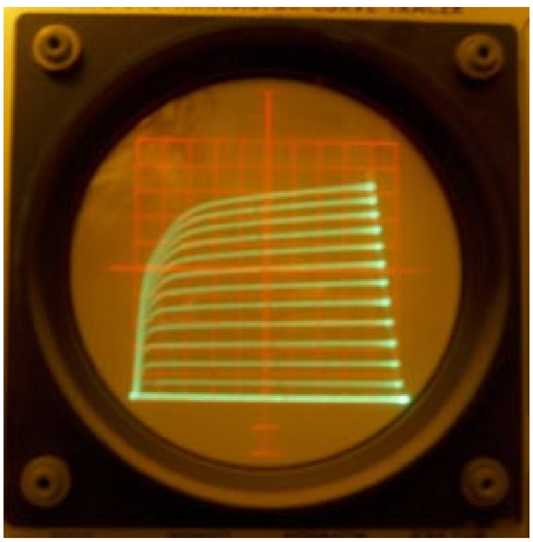

Fig. 1C - 2N4123

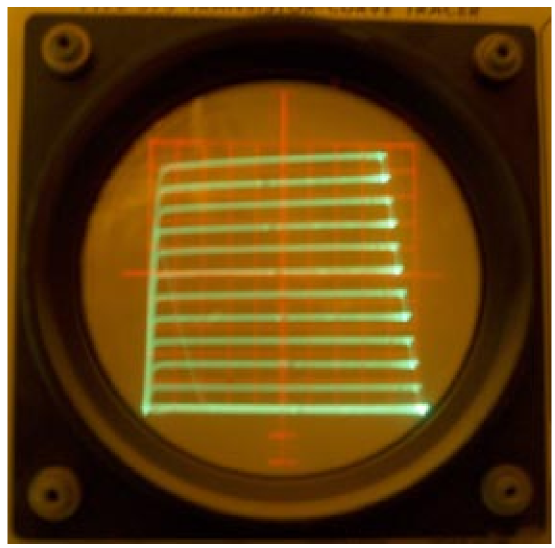

Fig. 1D - 2N4401

Fig. 1 - Curve families for various small-signal NPN bipolar transistors suitable for use in active antennas (20 µA/step, vertical - 5mA/division, horizontal - 1V/division)

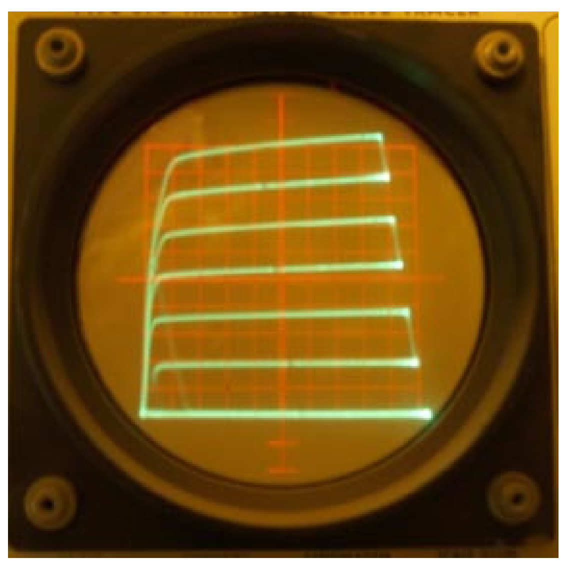

Fig. 1E - MPS6521

Device	V_{CEO}	P_D	h_{fe}	C_{cb}	C_0	f_t	NF	Price/Comments
2N2222 2N2219	40V	500mW 800mW	200	-----	8.0pF	300	1.5dB @ 1KHz	$0.10 to $0.25 (immortal) 2N2907 complement
2N3904	40V	625mW	200	-----	4.0pF	300	5.0dB	$0.08 (Mouseer) 2N3906 complement
2N4123	30V	625mW	120	-----	4.0pF	250	6.0dB	$0.06 (Mouser) 2N4125 complement
2N4401	40V	625mW	250	6.5pF	-----	250	2.0dB @ 1kHz	$0.09 (Mouser) 2N4403 complement
MPS6521	25V	625mW	450	-----	3.5pF	200	3.0dB	$0.10 (Mouser) MPS6523 complement

Table 1 - Static characteristics of small-signal NPN bipolar transistors suitable for active antenna applications

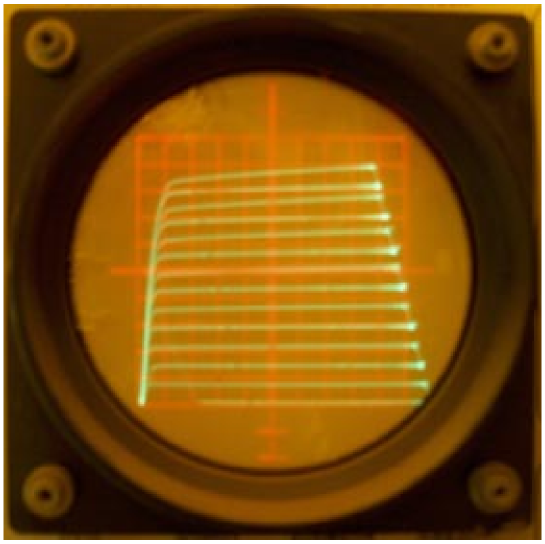

Fig. 2A - 2N3553

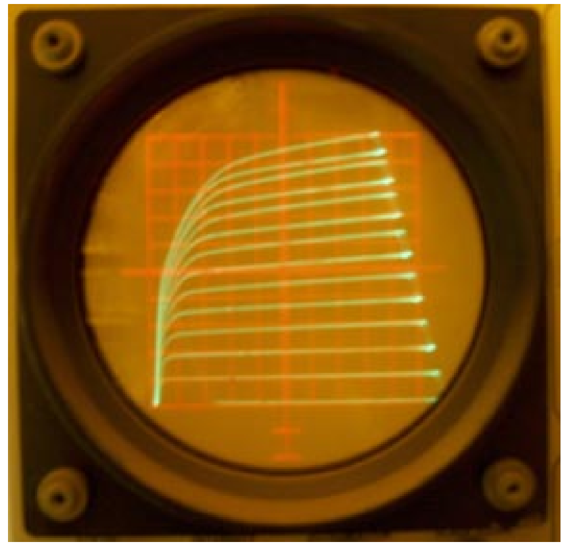

Fig. 2B - 2N3866

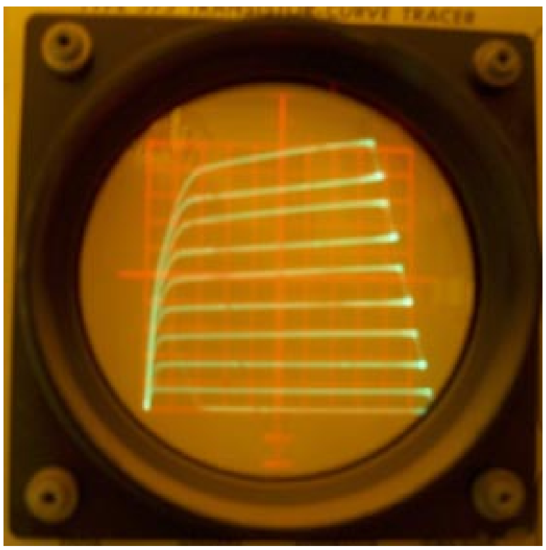

Fig. 2C - 2N4427

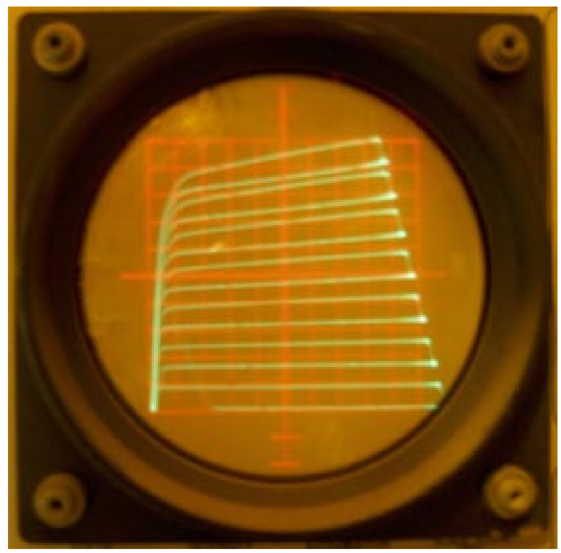

Fig. 2D - 2N5108

Fig. 2 - Curve families for various low-power NPN bipolar transistors suitable for use in active antennas (100 µA/step, vertical - 10mA/division, horizontal - 1V/division)

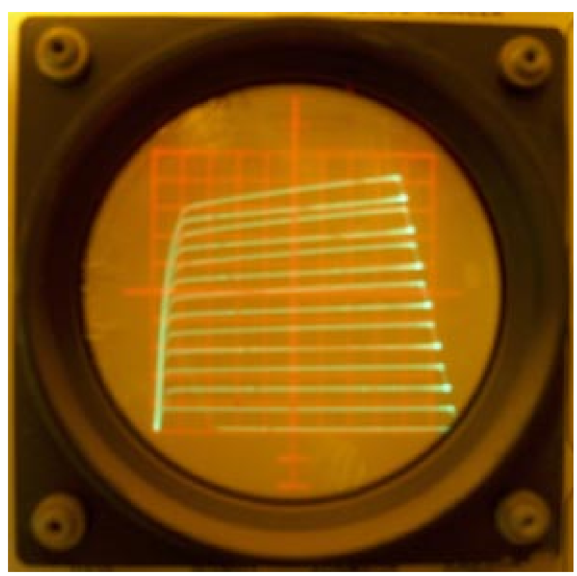

Fig. 2E - 2N5109

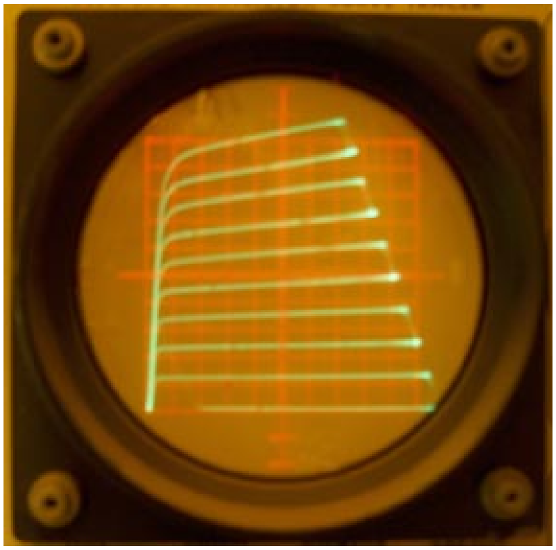

Fig. 2F - BFQ19

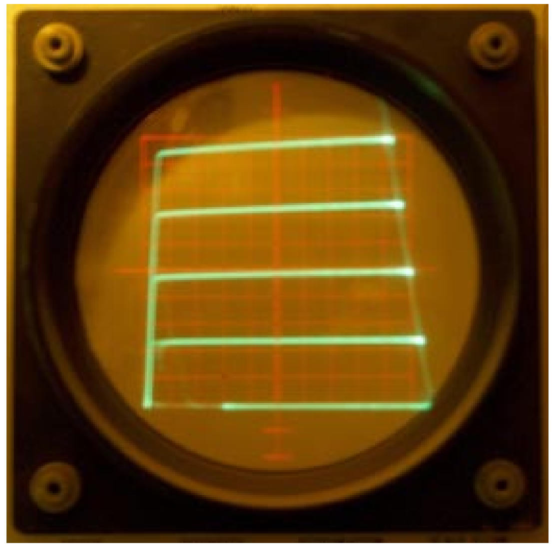

Fig. 2J - 2SC1568

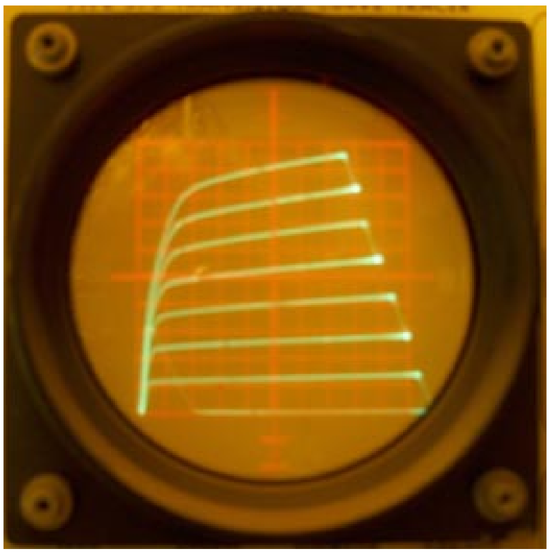

Fig. 2G - MRF581

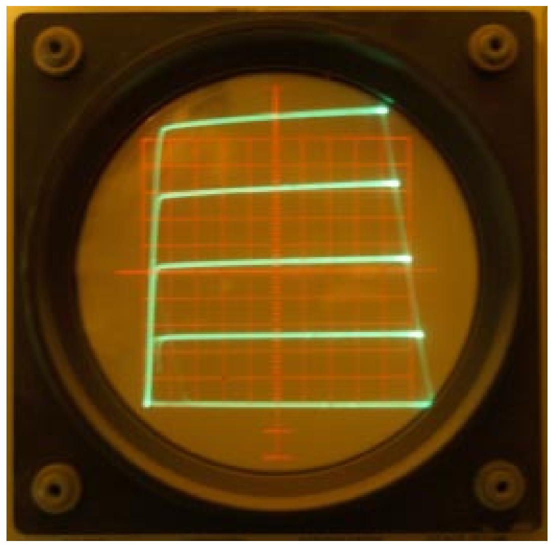

Fig. 2K - 2SC1846

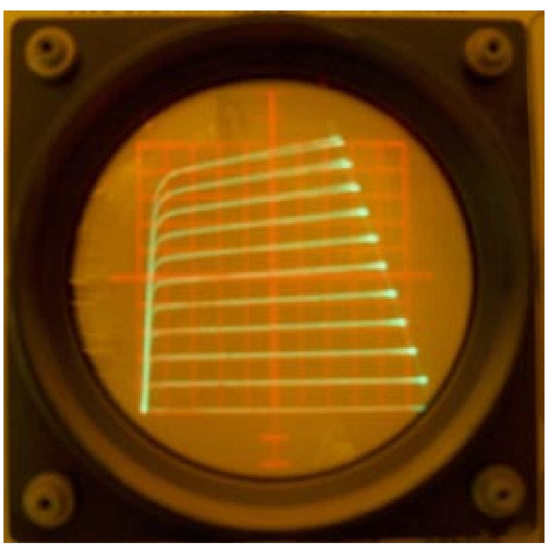

Fig. 2H - NE46134

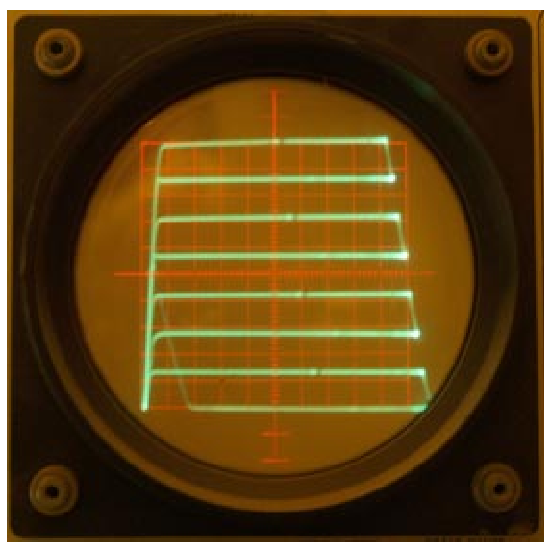

Fig. 2L - 2SC2497

Device	V_{CEO}	P_D	h_{fe}	C_{cb}	C_0	f_t	NF	Price/Comments
2N3553	40V	7.0W	75	-----	8.0pF	500	-----	$4.75 (RF Parts) Obsolete (ASI)
2N3866	30V	5.0W	100	-----	3.0pF	500	-----	$1.82 (Mouser) 2N5160 complement
2N4427	20V	3.5W	100	-----	4.0pF	500	-----	$2.21 (Mouser)
2N5108	30V	3.5W	80	1.5pF	1.3pF	1200	-----	unknown, obsolete (ASI)
2N5109	20V	2.5W	80	1.8pF	0.4pF	1200	3.0dB @ 200MHz	$1.87 (Mouser)
2SC1568R	18V	1.2W	170	-----	12pF	150	-----	$0.91 (Digi-Key)
2SC1846R	35V	1.2w	180	-----	20pF	200	-----	$0.55 (Digi-Key)
2SC2497R	50v	1.2w	180	-----	20pF	200	-----	$1.23 (Digi-Key)
BFQ19	15V	1.0W	80	1.3pF	1.6pF	5500	3.3dB @ 500MHz	$0.92 (Mouser) BFQ149 complement
MRF581	18V	1.8W	120	1.2pF	1.4pF	5000	2.0dB @ 500MHz	$3.95 (RF Parts, MRF581A) Obsolete (ASI)
NE46134	15V	2.0W	150	-----	-----	5500	1.5dB @ 500MHz	$1.73 (Mouser)

Table 2 - Static characteristics of various low-power NPN bipolar transistors suitable for active antenna applications

actually has a slight edge over the 2N2222 in the saturation and transition regions

At the same time, the 2N2222 has a slight edge over the 2N4401 in terms of NF, so the choice of these two device rests on the judgement of the designer as to whether IMD or NF performance is preferred.

The MPS6521 has considerably more gain than any of the other devices in this group, however its linearity degrades slowly for collector currents above 20mA. This, however, should not deter the designer from using this device as the higher gain is very desireable for emitter follower (aka common collector) applications.

Many other small-signal NPN devices are available for active antenna applications, the ones described herein having PNP complements that will be covered in a later section.

Low-Power NPN Devices

A series of eleven low-power NPN devices are described here, some currently available from Mouser, Digi-Key, and RF Parts and the remainder available from Advanced Semiconductor, having been obsoleted many years ago. Fig. 2 displays a series of characteristic curves for each device, while Table 2 lists some of the static characteristics as well as prices and sources for each.

The 2N3553 exhibits very good linearity with respect to other low and medium-low power candidate NPN devices, and it's unfortunate that it has been obsolete for quite some time. It is still available from Advanced Semiconductor, and can be purchased through RF Parts. The 2N3866 (28V operation) and 2N4427 (12V operation) are both usable below collector currents of 50mA, however the saturation region deteriorates rapidly above this point, especially for the 2N3866. Both of these devices are still available from Mouser at a fairly reasonable cost.

The 2N5108 and 2N5109 have been longtime standards of performance within the CATV industry, and they both show good characteristics in all three regions that need to be considered. The 2N5109 is still available from Mouser, however the 2N5108 is only available from Advanced Semiconductor and is undoubtedly very expensive.

The MRF581 has suffered the same fate but can be purchased from RF Parts for $3.95. Although it has fairly high gain, it's linearity leaves a lot to be desired. Even at collector currents as low as 40mA, it begins to show a degree of curvature in the linear region of the characteristic curves, after which the saturation and transition regions begin to deteriorate.

The BFQ19 (made by NXP née Philips) and the NE46134 (made by NEC) are both highly popular within the CATV industry, and are virtually identical in terms of linearity. They compare favourably to the 2N5109 in terms of linearity, though they pale in camparison with the 2N3553 (as do all the others). The saturation voltages remain low and the transition zones remain sharp even up to collector currents of 100mA. There is virtually no curvature of the traces in the linear region and the h_{fe} is essentially constant through this range of current. Both of these devices are available fro Mouser at reasonable prices.

Lastly, the 2SC1568, 2SC1846, and 2SC2497 devices display excellent linearity characteristics, with the first two also having exceptionally high gain. These devices, all available from Digi-Key at very reasonable prices, are in an all-plastic TO-126 case, which is very convenient as it eliminates the need for insulated spacers when mounting to a heat sink. They may also be mounted upside-down, which is of great benefit in laying out a single-sided

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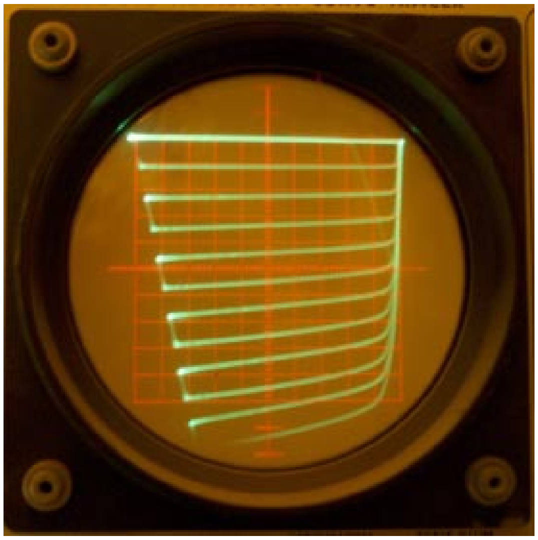

Fig. 3A - 2N2907

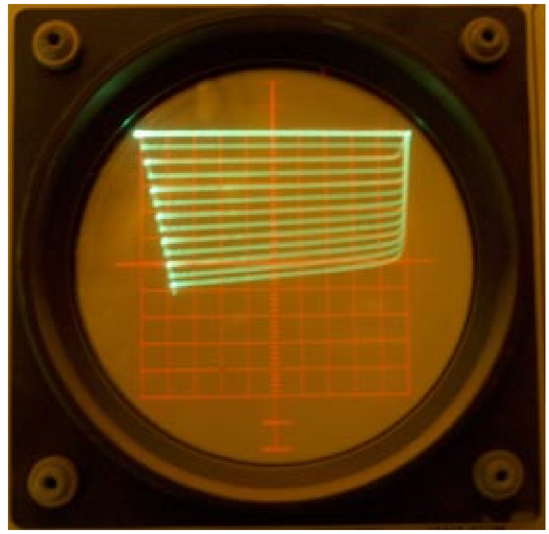

Fig. 3B - 2N3906

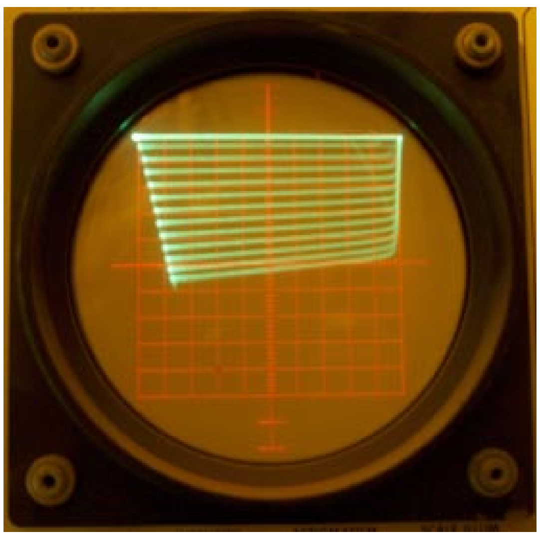

Fig. 3C - 2N4125

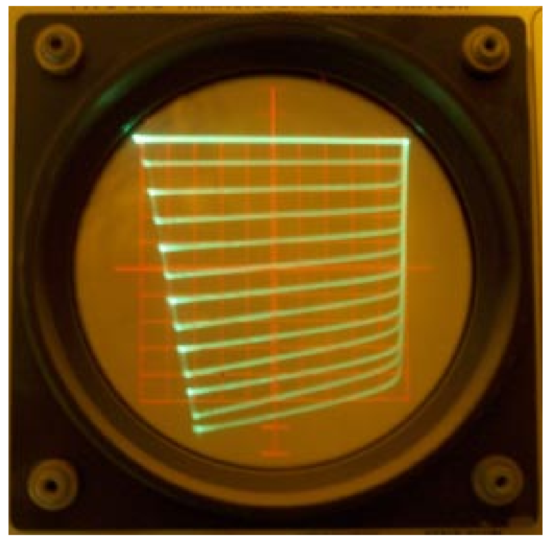

Fig. 3D - 2N4403

Fig. 3 - Curve families for various small-signal PNP bipolar transistors suitable for use in active antennas (20 μA/step, vertical - 5mA/division, horizontal - 1V/division)

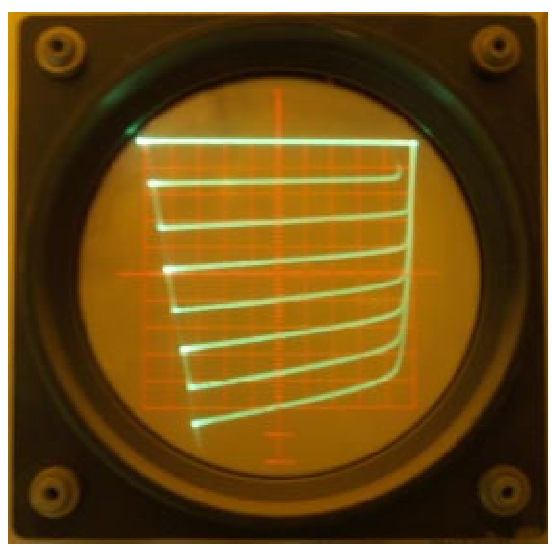

Fig. 3E - MPS6523

Device	V_{CEO}	P_D	h_{fe}	C_{cb}	C_0	f_t	NF	Price/Comments
2N2907 2N2905	40V	400mW 800mW	80	-----	8.0pF	200	-----	$0.10 to $0.25 (immortal) 2N2222 complement
2N3906	40V	250mW	150	-----	4.5pF	250	4.0dB	$0.07 (Mouser) 2N3904 complement
2N4125	30V	625mW	100	4.5pF	-----	200	5.0dB	$0.07 (Mouser) 2N4123 complement
2N4403	40V	625mW	150	-----	8.5pF	200	1.0dB	$0.10 (Mouser) 2N4401 complement
MPS6523	25V	625mW	450	-----	3,5pF	259	3.0dB	$0.10 (Mouser) MPS6521 complement

Table 3 - Static characteristics of various small-signal PNP bipolar transistors suitable for active antenna applications

PC board. These devies all have relatively low transition frequencies, so they are limited to mid-HF frequencies if used in common-emitter service, however they can be used throughout the entire HF spectrum when used as emitter followers and even into lower VHF frequencies when used as common-base amplifiers. Given the higher gain and excellent linearity characteristics of these devices, they should be given very serious consideration in HF design.

Small-Signal PNP Devices

A series of five small-signal PNP devices are described here, all of which are currently available from Mouser at very reasonable prices. Fig. 3 displays a series of characteristic curves for each of these devices, while Table 3 lists some of the static characteristics as well as prices and sources for each.

The first of these, the 2N2907, will probably arrive at the end of time hand-in-hand with the 2N2222. These two devices make a very good complementary pair and are ready available in their TO-92 plastic form, often for $0.05 or less. The 2N2222 and 2N2907 are virtually identical in terms of linearity characteristics, and because of this they make an excellent complementary pair at HF frequencies. The 2N2905 is essentially the same as the 2N2907, being the same die but in the larger TO-39 package which can dissipate more heat (800mW vs. 500mW) and which is more convenient in applications where a heat sink is desired.

The 2N3906 and 2N4125 have less gain than their NPN counterparts, being the 2N3904 and 2N4123, respecively. Still, for collector currents of less than 20mA they do make nice complementary pairs.

The 2N4401 and the 2N4403 display similar linearity characteristics, though not as closely as do the 2N2222 and the 2N2907. Still, the lower NF of a complementary pair of these devices should be taken into consideration.

The MPS6523 shows linearity characteristics identical to the MPS6521, making them a highly suitable complementary pair for emitter follower applications.

Low-Power PNP Devices

Very few low-power PNP devices have ever been available for RF design, in part due to the prejudice towards NPN devices that resulted from over a half century of vacuum tube circuit design, as well as the fact that very few designers consider PNP devices in RF design due to the overall lack of suitable devices plus the overriding penchant towards designs that incorporate only NPN devices.

At present, five PNP devices are worthy of consideration, listed in in Table 4 together with a series of characteristic curves in Fig. 4. The first of these devices, the 2N5160, is the PNP complement of the 2N3866, and displays the same deterioration in linearity for collector currents above 50mA. Furthermore, the device has been rendered obsolete as a consequence of the availability of better performing and less expensive devices. The 2N5160 is currently only available from Advanced Semiconductor, as part of their ever-growing line of replacement semiconductors. That product line grew substantially a few decades ago when Motorola suddenly decided that it was no longer going to be a participant in the discrete semiconductor market. The 2N5160 now costs around $US10 each in small quantities, and will likely increase as the demand for replacement devices such as this naturally decreases with time.

The second of the low-power PNP devices is the BFQ149 (made by NXP), which is the complement to the BFQ19. Although the BFQ149 does not have the exact linearity characterists of the BFQ19, it compares favour-

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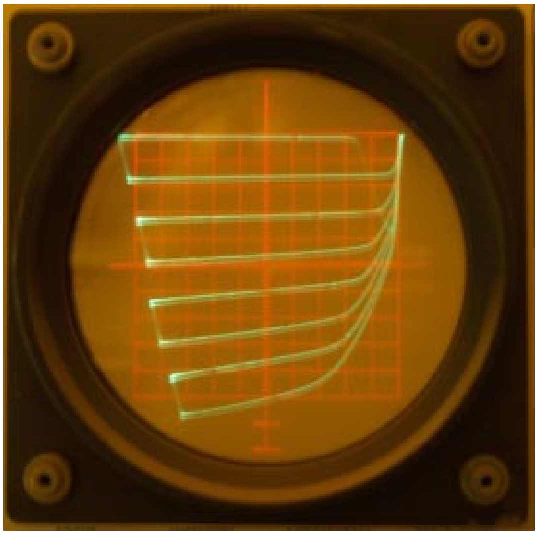

Fig. 4A - 2N5160

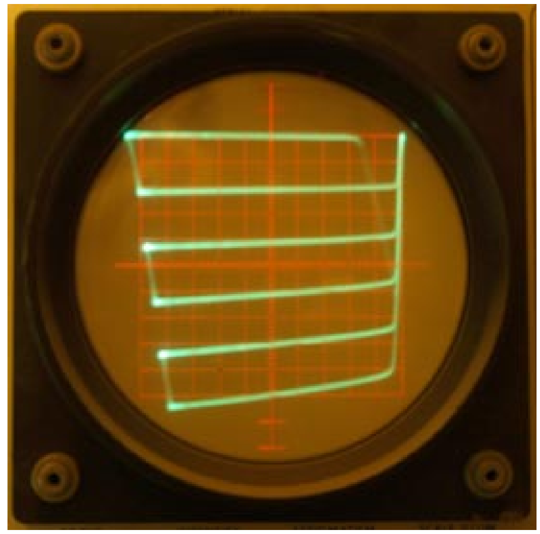

Fig. 4C - 2SA0885

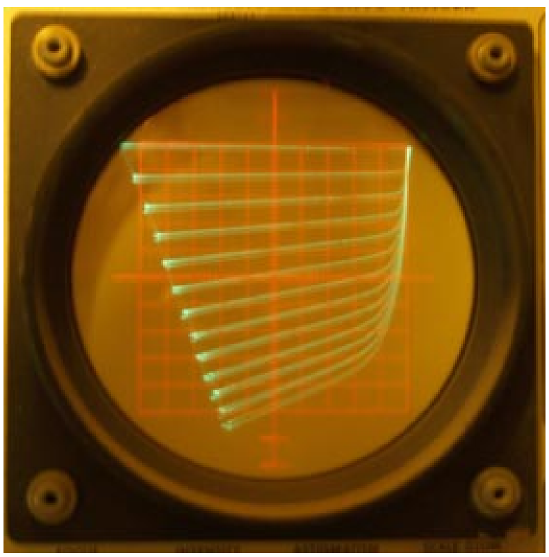

Fig. 4B - BFQ149

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SOON

Fig. 4D - 2SA0900

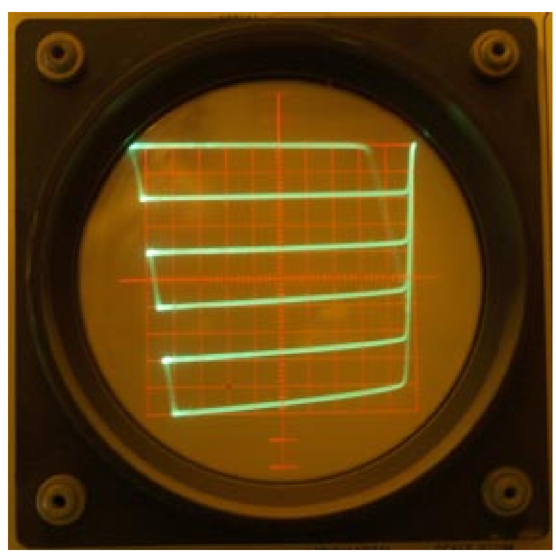

Fig. 4E - 2SA1096

Fig. 4 - Curve families for various low-power PNP bipolar transistors suitable for use in active antennas (100 µA/step, vertical - 10mA/division, horizontal - 1V/division)

Device	V_{CEO}	P_D	h_{fe}	C_{cb}	C_0	f_t	NF	Price/Comments
2N5160	40V	5.0W	150	2.5pF	-----	900	-----	$10 (obsolete, ASI) 2N3866 complement
2SA0885R	40V	1.2W	170	-----	45pF	150	-----	$0.63 (Digi-Key) 2SC1846R complement
2SA0900R	18V	1.2W	170	-----	40pF	200	-----	$1.13 (Digi-Key) 2SC1568R complement (discontinued)
2SA1096R	50V	1.2W	170	-----	55pF	150	-----	$1.10 (Digi-Key) 2SC2497R complement
BFQ149	15V	1.0W	100	1.7pF	2.0pF	5000	3.75dB @ 500MHz	$1.13 (Mouser) BFQ19 complement

Table 4 - Static characteristics of various low-power PNP bipolar transistors suitable for active antenna applications

ably with the 2N5160, even more so when price and availability are taken into consideration. Together, with the higher gain, improved linearity and NF, and higher transistion frequencies, these two devices create a complementry pair that has no equal in RF design.

The remaining three devices, the 2SA0885, 2SA0900, and 2SA1096 are complements of the 2SC1846, 2SC1568, and 2SA2497, respectively, though it needs to be pointed out that the 2SC0900 has been discontinued. Just as with their NPN counterparts, these devices are made by Panasonic and are available fro Digi-Key at very reasonable prices. Though not having the excellent linearity characteristics of their NPN counterparts, these devices still display linearity characteristics well above those of the other low-power PNP devices discussed here. In addition, their lower transistion frequencies make them suitable for VLF/LF to mid-HF frequencies in common-emitter configurations as well as the entire HF spectrum and possibly lower VHF when used as common-base amplifiers, and with the higher gain and very good linearity characteristics of these devices, they should be given very serious consideration in HF design, especially for applications requiring complementary pairs.

Synopsis

When choosing a bipolar transistor for an active antenna design, it is very important that the device be currently in production and readily available through popular distributors such as Mouse and Digi-Key. Devices that have been rendered obsolete and of limited availability at accelerated prices can only discourage builders.

In regard to technical aspects, NF and IMD performance are most important and their consideration needs to be adjusted for the frequency range of consideration. For frequencies at HF and below, NF becomes less important due to the incrasing presence of terrestrial and galactic background noise as frequency decreases. At the same time, IMD performance becomes more important due to the crowding in the various broadcasting bands (BCB), especially that of MW frequencies as these high-power signals can generate harmonics in poorly designed amplifiers that will appear in the SWBC bands of the receiver.

Above HF frequencies, NF becomes increasingly important as the receiver NF will rise above the terrestrial and galactic background noise seen by the antenna. As this paper has been primarily focused on active antenna designs for HF frequencies and below, there has been little emphasis on this finer point of device selection.

The graphical presentation of device characteristics is the primary source for judging device linearity. From this form of data, the saturation region, transition region, and linear region characteristics of a device can be easily observed. Even so, only direct experience in equating these characteristics with amplifier performance will bring the designer to forming a basis for judgement.