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AR-002

Amateur Radio Application Note

AN IMPROVED BIAS TEE FOR 1.8-30.0 MHz

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I INTRODUCTION & OVERVIEW

A bias Tee is a device that allows DC voltage to be injected into the antenna feed line for the purpose of remote antenna switching and/or antenna band switching. This bias Tee must accomplish two primary objectives. First, it must prevent the DC voltage from backing up into the transceiver. This is accomplished using a suitable series capacitor as a DC block at the RF input terminal. This capacitor must have very low reactance at the lowest operating frequency (i.e., 1.8 MHz for the HF range), as well as very low inductance at the highest frequency (30.0 MHz for HF). For high power applications, this capacitor must have a high RF current rating.

Second, the DC voltage must be introduced into the feed cable through an isolation choke that offers a very high impedance throughout the antenna operating frequency range (i.e., the choke impedance must be much greater than the nominal feed cable impedance). For high power applications, this choke must have a high voltage rating as well. Additionally, this choke must be able to handle the maximum expected DC current without saturation. (Saturation reduces effective choke impedance and thus choke effectiveness.)

Although bias Tees for amateur radio are available from several manufacturers, the models I studied have significant design compromises (especially for high power applications). For this reason, I designed and constructed my own as described in detail in the following Sections.

The bias Tee circuitry is straightforward as illustrated the Figure 2 schematic. The RF (DC block) J1 input is connected to the transceiver. The RF (DC pass) J2 output is connected to the antenna. The DC control voltage is connected to the J3 bias input port. All three inputs/outputs are ground referenced.

Although the circuit is simple, it did require some thought to implement as well as careful component selection and additional care and attention to detail for safe performance at 1,500 watts.

The circuit was built into the housing of an MFJ-4712RC antenna selector switch remote control unit illustrated in Figure 1. This unit employs a bias Tee to apply the switch selection voltage thru the coaxial cable and up to the antenna switching unit. MFJ claims that this unit will handle up to 1,500 watts from 1-150 MHz, but I was skeptical that it could do this reliably. My primary concern was that the isolation was not adequate for the intended application. Although I salvaged nearly all the MFJ-4712RC parts (including the case), I had to include additional isolation chokes as discussed below.

Figure 1 - MFJ-4712RC Antenna Switch Remote Control Unit

Visit my N6DC vintage and amateur radio website at www.rdfproducts.com/n6dc.htm for possible revisions to this paper. This website hosts a variety of vintage and amateur radio technical papers.

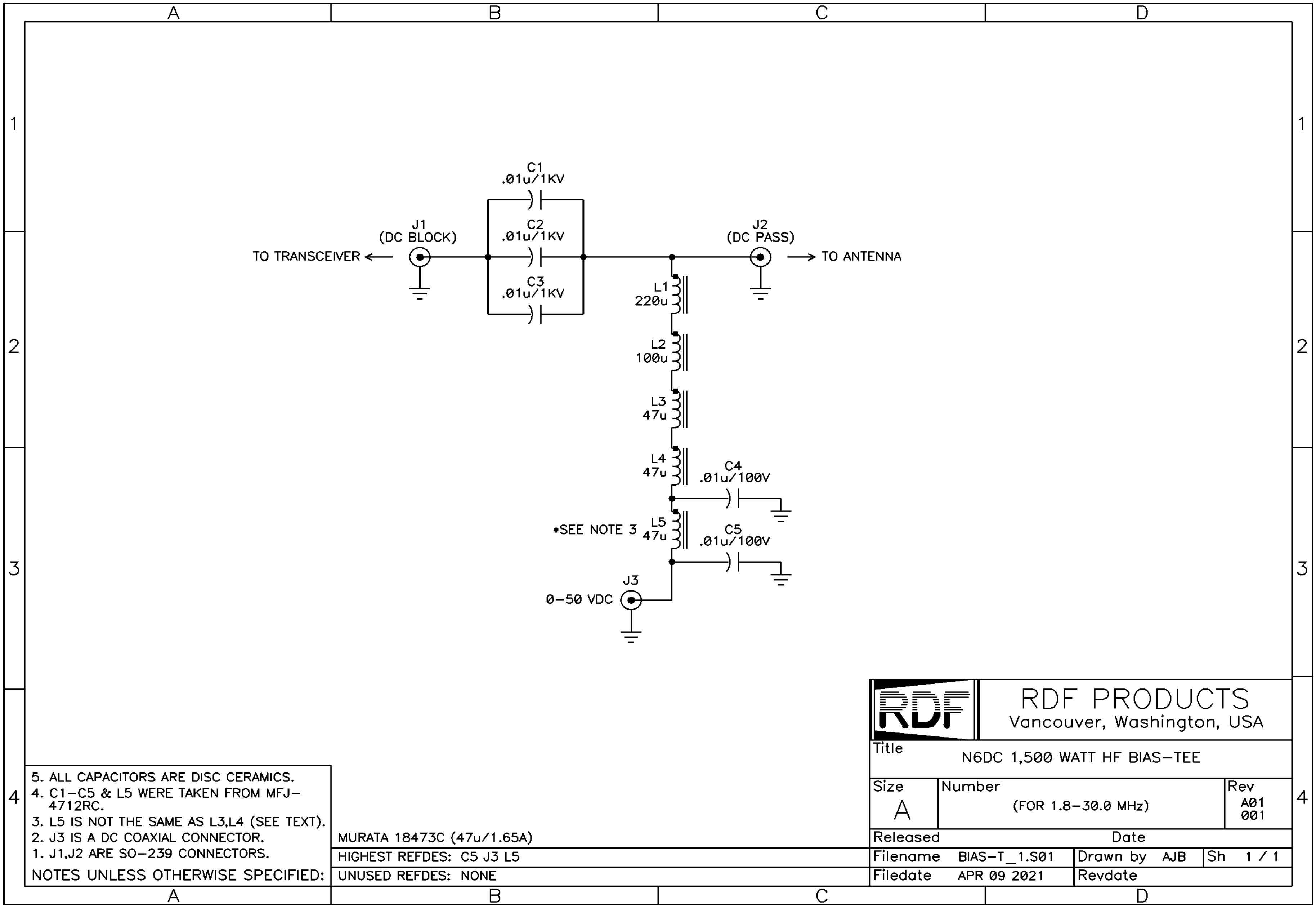


Figure 2 - Schematic for Improved Bias Tee

II DESIGNING AN IMPROVED BIAS TEE ISOLATION CHOKE

Fundamentally, the bias tee isolation choke must present an impedance at the operating frequency that is much higher than the line impedance (typically 50 ohms). When this condition is met, RF currents flowing thru the choke are negligible compared to the RF current flowing in the transmission line. Although that seems easy enough to accomplish, there are some complications:

1. The isolation choke impedance must be very high at *all* operating frequencies of interest.

2. The isolation choke must be able to handle whatever RF currents flow into it. Although these currents must be “negligible”, this is relative to the transmission line current. At 1,500 watts, even “negligible” RF current can be large enough to burn up a choke not selected with this requirement in mind.

3. The isolation choke must have a voltage rating suitable for the station RF power levels. While this is usually not an issue for 100 watts, it can be a major problem for 1,500 watts.

4. The isolation choke must be able to handle the required DC current without saturating. This is not an issue for air wound chokes, but chokes employing ferrite or iron powder cores have saturation current limitations that must be observed.

I noticed that the isolation choke used in the MFJ-4712RC was a 47 uH Murata 18473C power inductor (used in switching power supplies). I looked up its specifications and found it to be an excellent candidate for use as an isolation choke for the following reasons:

1. It is rated at up to 1.65 amperes DC (without saturating).

2. Its DC resistance is very low (55 milli-ohms).

Since power inductors in general have specified maximum current ratings, there is no guesswork as to their current handling capacity. This is in contrast to other iron powder or ferrite inductors that do not have specified saturation current ratings. This is an important advantage favoring power inductors for use as isolation chokes.

Although this Murata inductor line has been discontinued, it gave me the idea to investigate similar power inductors as candidates for an isolation choke. As it happens, Murata manufactures an alternative version of the 18473C. This replacement model is the 32470C, which is also 47 uH, is rated at up to 2.1 amperes, has a DC resistance of 42 milli-ohms, and has significantly less inter-winding capacitance (which is a positive quality for an isolation choke).

As per Figure 3, the 32470C is a vertical-mount toroidal inductor. Although physically larger than the discontinued 18473C, it is a better part. Finally, it is available in a wide variety of values from 10 uH up to 1000 uH. This is important since different values provide different isolation frequency response.

Figure 3 - Murata Toroidal Power Inductor (150 uH)

For good isolation over a wide frequency range, I found it necessary to series cascade multiple chokes in order to obtain the desired isolation. This in turn raises the important issue as to how to evaluate the choke’s impedance over a specified frequency range.

Fortunately, there is a straightforward test setup for this measurement. Referring to Figure

4, we can insert the choke into a 50 ohm line, observe the dB insertion loss over the frequency range of interest using a network analyzer, and then convert this measured attenuation into impedance at any given frequency computationally.

Procedurally (and still referring to Figure 4), we connect the network analyzer sweep generator output probe to J1 and its detector probe to J2. To calibrate the fixture, we bridge the test terminals with a direct short (i.e., a short length of wire) and then conduct a frequency sweep over the range of interest. This establishes a 0 dB loss reference as indicated on the network analyzer display.

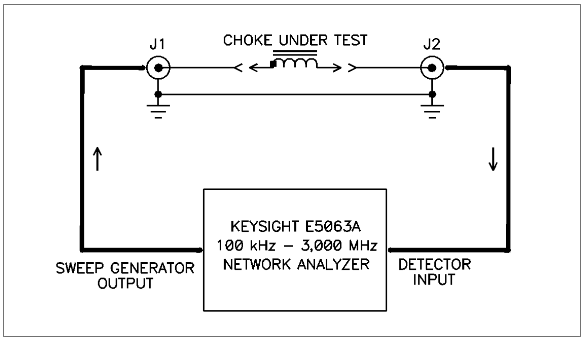


Figure 4 - Choke Impedance Test Fixture

Next, we remove this short and replace it with the choke under test, and again conduct the frequency sweep. This results in the sweep displaying varying levels of insertion loss over the frequency range of interest.

Finally, we compute the insertion loss at selected frequencies of interest (i.e., in the amateur bands) using the following equation (presented here in QBASIC code format):

```
Rs = 2 * Zo / ((2.718282 ^ (-dB / (20 / 2.302585093)))) - 2 * Zo
```
(1)

where:

Rs = computed resistance value
Zo = line impedance (typically 50 ohms)
dB = measured dB insertion loss at the frequency of interest (entered as a positive number)

As an example, for a measured insertion loss at a selected frequency of interest is 20 dB, the effective resistance value is computed at 900 ohms using equation (1) above. This would provide good isolation for most applications.

To simplify this computation for the reader, I have written a computer program (RDFUTIL1.EXE). This program can be downloaded from the N6DC website. (After opening the program, follow the instructions and then select Main Menu option #23.)

The astute reader will point out that the above equation computes resistance whereas an actual isolation choke will be nominally inductive. As a result, the reader might wonder if this might affect computational accuracy. This is a fair point and requires an explanation.

In the general case, a choke can be modeled at any given frequency as an inductor, capacitor, and resistor (LCR) in series. The inductive component is obvious enough and requires no explanation. The capacitive component results from the choke inter-winding (distributed) capacitance. The resistive component results from inductor losses (i.e., the inductor cannot have infinite Q).

Returning to the computational accuracy issue, equation (1) is actually an approximation using the simplifying assumption that the choke is purely resistive. While this results in significant errors for chokes having low insertion loss, this error diminishes rapidly as the insertion loss increases. For chokes exhibiting values of insertion loss high enough to be useful, this error is negligible. Equation (1) is thus a good engineering approximation in the applications for which it is useful.

To illustrate the above concepts by practical example, the Figure 4 test fixture was constructed and then calibrated using a 0 ohm resistor (i.e., a short wire) as the “choke under test” to create a 0 dB insertion loss reference.

Next, the short wire was removed and replaced with a 900 ohm resistor. As per Figure 5, the measured insertion loss at the amateur band marker frequencies was very close to 19.9 dB, which is in excellent agreement with the 20 dB computed value from equation (1) above.

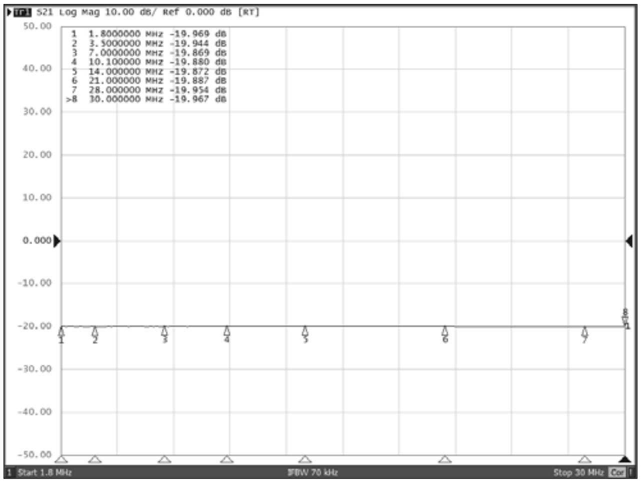


Figure 5 - 1.8-30.0 MHz Swept Insertion Loss for 900 Ohm Resistor

Figure 6 shows the swept frequency response for a Murata 32101C 100 uH inductor. This response illustrates some important concepts regarding inductor behavior over frequency.

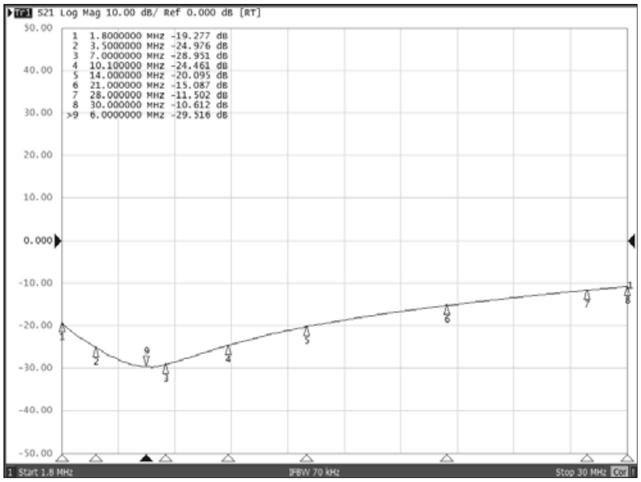


Figure 6 - 1.8-30.0 MHz Swept Insertion Loss for Murata 32101C 100 uH Inductor

First, notice that from 1.8-6.0 MHz the curve is down-sloping (i.e., the insertion loss increases monotonically in this frequency range). This is the behavior that we would expect for a series inductor.

Notice also that the insertion loss is maximum at 6.0 MHz. This occurs because the inductor becomes parallel resonant at that frequency (i.e., the inductance and inter-winding capacitance are resonant at 6.0 MHz). At this resonant frequency, the inductor is purely resistive.

Finally, notice that from 6.0-30.0 MHz the curve is up-sloping (i.e., the insertion loss decreases monotonically). This occurs because the inductor appears net capacitive in this frequency range.

The point of this discussion is that inductors are actually LCR components that are not purely inductive at all frequencies. This important point must be kept in mind when designing a wideband isolation choke.

Figure 7 shows the swept frequency response for a Murata 32470C 47 uH inductor. It is similar to that of the 100 uH inductor but with higher (better) insertion loss in the higher portion of the frequency range as one would expect.

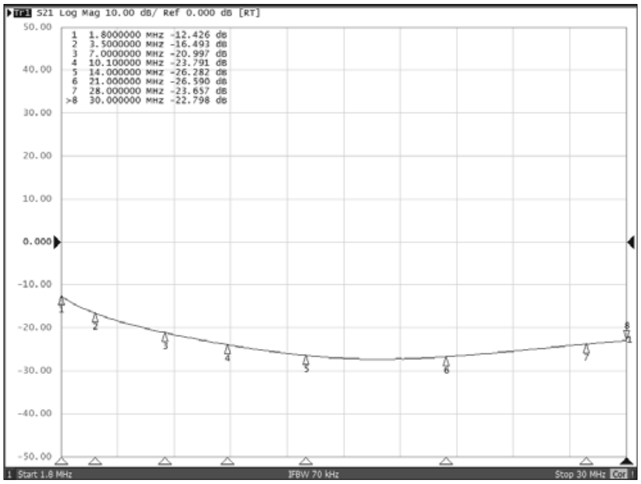
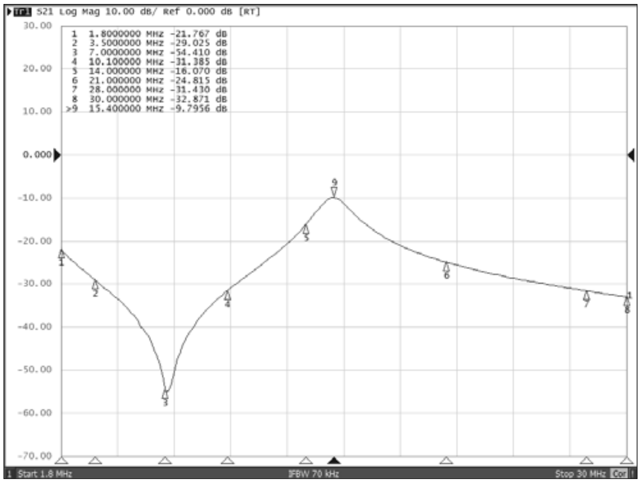


Figure 7 - 1.8-30 MHz Swept Insertion Loss for Murata 32470C 47 uH Inductor

Figure 8 shows the swept insertion loss for the isolation choke used in the MFJ-4712 antenna switch unit. (Note that this is a different inductor than the Murata 47 uH inductor used in the MFJ-4712RC remote controller unit.)

This isolation choke is not identified in the MFJ-4712 parts list. However, as can be seen from Figure 8, this choke exhibits a sharp parallel resonance near 7.0 MHz and a sharp series resonance at 15.4 MHz. Based on this frequency response, this choke is not well-suited for its intended application.



```
 1   1.8000000 MHz -21.767 dB
 2   3.5000000 MHz -29.025 dB
 3   7.0000000 MHz -54.410 dB
 4   10.100000 MHz -31.385 dB
 5   14.000000 MHz -16.070 dB
 6   21.000000 MHz -24.815 dB
 7   28.000000 MHz -31.430 dB
 8   30.000000 MHz -32.871 dB
>9   15.400000 MHz -9.7956 dB
```

Figure 8 - 1.8-30 MHz Swept Insertion Loss for MFJ-4712 Remote Switch Inductor

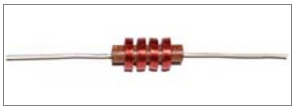
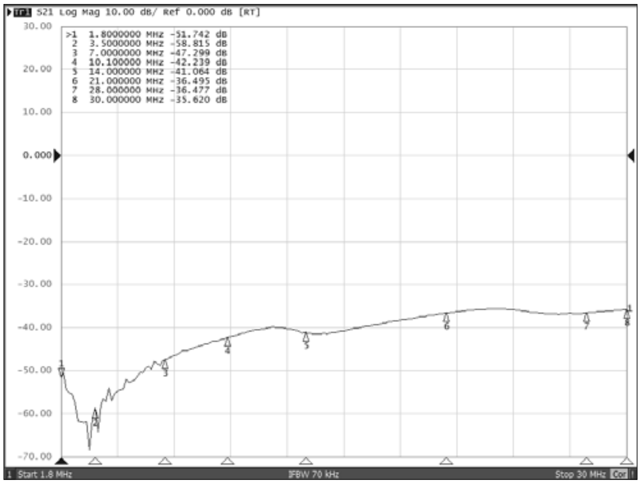


Figure 9 - 2.5 mH Pi-Wound RF Choke

To put the performance of this MFJ choke in perspective, I tested a classical 1930's technology pi-wound 2.5 mH RF choke (see Figure 9) specifically designed for the 1.8-30.0 MHz range.

As per Figure 10, this choke provides truly exceptional isolation (> 35 dB) over the full frequency range. The multi-section pi winding technique was developed specifically to minimize inductor inter-winding capacitance. This greatly mitigated the problems caused by self-resonances that degrade the MFJ choke as per Figure 8.

Based on the performance illustrated in Figure 10, one would think that the 2.5 mH pi-wound choke would be the ideal isolation choke and that we would need to look no further. Unfortunately, this is not the case.



```
>1   1.8000000 MHz -51.742 dB
 2   3.5000000 MHz -58.815 dB
 3   7.0000000 MHz -47.299 dB
 4   10.100000 MHz -42.239 dB
 5   14.000000 MHz -41.064 dB
 6   21.000000 MHz -36.495 dB
 7   28.000000 MHz -36.477 dB
 8   30.000000 MHz -35.620 dB
```

Figure 10 - 1.8-30.0 MHz Swept Insertion Loss for Wilco 2.5 mH Pi-Wound RF Choke

First, these chokes have been out of production for 50 years or so, and can be obtained only thru after-market channels at excessive prices. Second, the current rating is limited. While RF Parts (the source for this choke) claims that the Wilco RF choke of Figure 9 can handle 500 mA, this is doubtful. At 500 mA, this choke overheats to the point where its wax begins to melt. A more realistic current rating would be 200 mA. Also, with a 24 ohm winding resistance, the voltage drop across this choke is somewhat high.

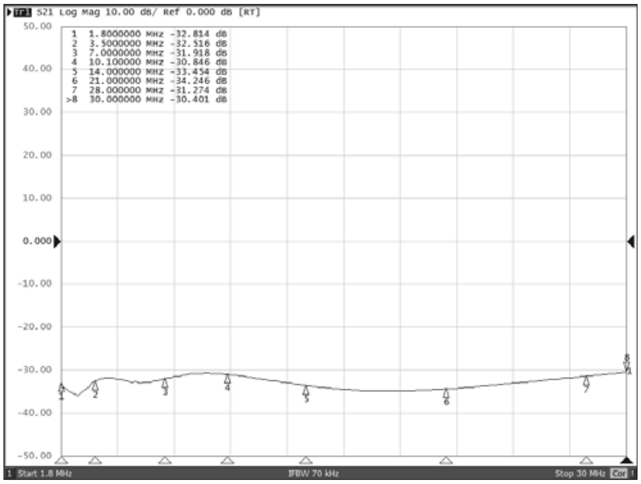
Even with these drawbacks, this and similar classical RF chokes can be useful in some applications. However, given that they are out of production, they are not a modern solution. The greater purpose of this discussion, however, is to point out that isolation chokes found in modern day amateur radio equipment are often a pale imitation of what was accomplished nearly a century ago. This exercise also gave me valuable insight as to what is possible with good component design techniques.

At this point, I decided that the Murata 32xxxC-series power inductors were the most promising candidates for a high performance isolation choke, based on their very high current handling capability, low resistance, low inter-winding capacitance, and absence of sharp resonances. Since these conductors exhibit somewhat high Q, however, it was evident that a single inductor would provide good isolation over only a portion of the 1.8-30.0 MHz spectrum.

This being the case, my next thought was to place two or more of these inductors in series to achieve more isolation. This turned out *not* to be a straightforward procedure and required a great deal of experimentation.

The final result comprised four inductors in series (in the order illustrated in the Figure 2 schematic) to provide the isolation illustrated in Figure 11. These inductors are as follows:

47 uH (2 ea.); Murata P/N 32470C
100 uH (1 ea); Murata P/N 32101C
220 uH (1 ea); Murata P/N 32221C



```
S21 Log Mag 10.00 dB/ Ref 0.000 dB [RT]
 1   1.8000000 MHz -32.814 dB
 2   3.5000000 MHz -32.516 dB
 3   7.0000000 MHz -31.918 dB
 4   10.100000 MHz -30.846 dB
 5   14.000000 MHz -33.454 dB
 6   21.000000 MHz -34.246 dB
 7   28.000000 MHz -31.274 dB
>8   30.000000 MHz -30.401 dB
```

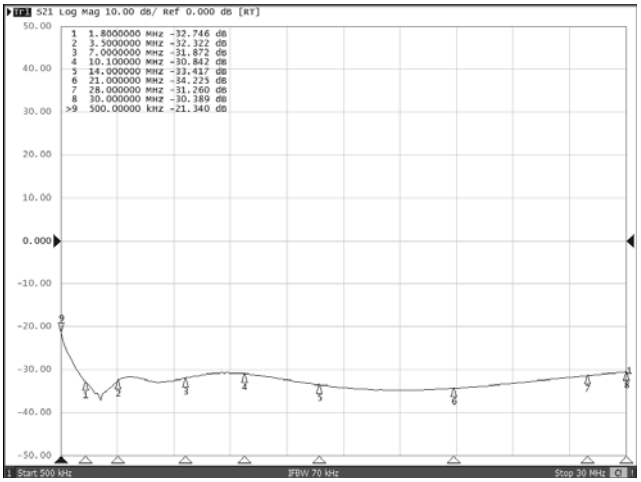
Figure 11 - 1.8-30 MHz Insertion Loss for 47 uH/47 uH/100 uH/220 uH Inductors in Series (see text)

These inductors are all available from Mouser Electronics, Inc. as well as other suppliers.

As per the Figure 12 insertion loss graph, results are excellent with insertion loss greater than 30 dB at all frequencies. This corresponds to a choke impedance of over 3,000 ohms using equation (1) above, which results in negligible loading on a 50 ohm line.

Since I am also interested in AM broadcast band DXing, I ran another sweep extending the low-end frequency boundary down to 500 kHz (i.e., just below the AM broadcast band). As per Figure 12, the insertion loss at 500 kHz is 21.34 dB, corresponding to a very respectable impedance of over 1,000 ohms using equation (1) above.

For those readers not having access to a network analyzer, a good alternative would be a suitable hand-held antenna analyzer (e.g., the Rig Expert AA-55 Zoom).



```
S21 Log Mag 10.00 dB/ Ref 0.000 dB [RT]
 1   1.8000000 MHz -32.746 dB
 2   3.5000000 MHz -32.322 dB
 3   7.0000000 MHz -31.872 dB
 4   10.100000 MHz -30.842 dB
 5   14.000000 MHz -33.417 dB
 6   21.000000 MHz -34.225 dB
 7   28.000000 MHz -31.260 dB
 8   30.000000 MHz -30.389 dB
>9   500.00000 kHz -21.340 dB
```

Figure 12 - 0.5-30.0 MHz Insertion Loss for 47 uH/47 uH/100 uH/220 uH Inductors in Series (see text)

III MORE THOUGHTS & RECOMMENDATIONS FOR BIAS TEE ISOLATION CHOKES

Readers designing their own isolation chokes may wonder what minimum choke impedance is required for good performance. There is no precise answer to this reasonable question, and it also depends upon the transmitter power output (i.e., a choke with marginal impedance can be better tolerated for a transmitter power output of 100 watts than would be the case for 1,500 watts).

As a minimum, we would not want the choke to load the transmitter output to the extent where it would significantly change the antenna system VSWR. (The choke is effectively in parallel with the transmission line near the transceiver end.) As a case in point (and again invoking the simplifying assumption that the choke impedance is resistive), if the antenna VSWR is 1.0:1 and a 500 ohm choke is added to the system, the VSWR will rise to 1.1:1 in a 50 ohm system. This is acceptable in any practical application. A 500 ohm choke would correspond to a choke insertion loss of approximately 16 dB in the 50 ohm line test fixture of Figure 4. However, 10% of the total RF current would flow into the choke which would be an issue for a high power application.

If I had to put a number on this, I recommend at least 16 dB of isolation for a 100 watt transmitter. I think a safer number is 20 dB, which would correspond to an impedance of 900 ohms. Applying the same VSWR variation exercise, the VSWR would rise to 1.06:1 with 5.6% of the total RF current flowing into the 900 ohm choke. For high power applications up to 1,500 watts, I recommend 30 dB minimum.

Table I below lists choke impedance for various insertion loss values for convenient reference.

Table I - Choke Impedance versus dB Insertion Loss

dB Insertion Loss	Impedance (ohms)	dB Insertion Loss	Impedance (ohms)
15	462	31	3448
16	531	32	3881
17	608	33	4367
18	694	34	4912
19	791	35	5523
20	900	36	6210
21	1022	37	6980
22	1159	38	7843
23	1313	39	8813
24	1485	40	9900
25	1678	41	11120
26	1895	42	12489
27	2139	43	14025
28	2412	44	15749
29	2718	45	17683
30	3062	46	19853

IV CONSTRUCTION DETAILS

Referring to the Figure 2 schematic, I was able to fit all the bias Tee circuitry on a small 100 mil grid single-sided copper-clad perf board that fits snugly inside the MFJ-4712RC evaluation unit housing. As a bonus, I was able to salvage most of the parts from this unit.

As per Figure 13, I retained the SO-239 RF In/Out connectors since these were good quality parts. Since there was no longer any need for the ANT 1/ANT 2 switch, I removed it and covered the hole with a small piece of PC board material.

I also replaced the DC coaxial connector with a premium grade version (i.e., one that accepts a threaded locking mating plug). I use this as a standard connector for my station since it is more rugged and durable than the non-locking versions, but the original MFJ connector is adequate.

Figure 13 - N6DC Bias Tee Topside View (bottom cover removed)

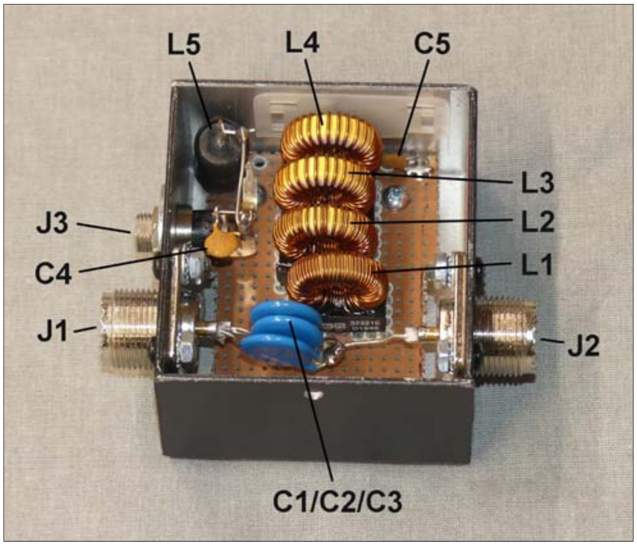


Figure 14 - N6DC Bias Tee Underside View (bottom cover removed)

Figure 14 shows all the components (bottom cover removed). All of the original MFJ electronic components were salvaged. L5 (the MFJ 47 uH isolation choke) was replaced by the four Murata 32xxxC-series toroidal inductors as discussed in Section II. L5 (the original MFJ isolation choke) was re-purposed as a decoupling choke as per the Figure 2 schematic. C1, C2, and C3 are the original MFJ .01u/1kV DC blocking capacitors, and C4 and C5 are the original MFJ .01u/100V decoupling capacitors.

The redesigned unit works very well throughout the entire 160-10 meter range (and even down to 500 kHz for receive-only applications). It can handle 1,500 watts safely and exhibits negligible loading and insertion loss.

V SUMMARY & CONCLUSION


Figure 15 - Fully Assembled N6DC Bias Tee

A bias Tee is a device that allows DC voltage to be injected into the antenna feed line for the purpose of remote antenna switching and/or antenna band switching. It comprises two primary components. The first is a series coupling capacitor to prevent the DC voltage from backing into the transceiver. The second is a high impedance shunt choke to isolate the DC voltage source from the RF path to prevent unintended loading.

Of these two components, the isolation choke is the most difficult to select or construct and evaluate. Although bias Tees are available from a number of amateur radio equipment manufacturers, the isolation chokes employed in these units are marginal to poor for the claimed frequency coverage and transmitter power levels.

The primary issue limiting choke performance is its inter-winding (distributed) capacitance. This can result in resonances which can badly degrade choke performance over the desired frequency range. As a result, selecting or constructing a choke with high impedance over a wide frequency range is not a straightforward task.

A related issue is that of choke DC saturation. For chokes employing iron powder or ferrite cores, the DC current can saturate the core and thereby degrade performance. A further complicating issue is that the maximum choke current that can be handled without DC saturation is often unspecified and difficult to determine empirically.

Isolation choke impedance can be readily determined by inserting the choke in series in a 50 ohm transmission line and then measuring its insertion loss (attenuation) over the desired frequency range using a network analyzer. This measured insertion loss can then be converted into impedance at any given frequency computationally using a straightforward equation.

The required minimum impedance depends upon the acceptable loading of the RF signal path. It also depends upon the RF power level since high power can result in significant RF current flowing thru the choke and possible choke damage.

Power inductors used in switching power supplies are good candidates for use as isolation chokes. They are designed for low inter-winding capacitance and have specified DC saturation current ratings (which are typically high).

Although no single inductor will yield good isolation over a very wide range, multiple inductors can be series cascaded to achieve improved performance. Although this process is not straightforward and requires experimentation, the 50 ohm transmission line test setup facilitates this trial and error process. By this means, an effective solution was achieved with excellent isolation over the 1.8-30.0 MHz range using four Murata toroidal power inductors wired in series. For receive-only applications this solution yields good results down to 500 kHz (i.e, just below the low end of the AM broadcast band).

The complete bias Tee circuit was built into the housing of an MFJ-4712RC antenna selector switch remote control unit as illustrated in Figure 15. Nearly all of the original components were salvaged, with the primary change being the addition of the four Murata power inductors to replace the original MFJ isolation choke. The unit performs well and handles power levels up to 1,500 watts. <>