APPLICATION NOTE

The Bird BNA Series
RF Filter Characteristics

Making Filter Measurements Using the Bird Vector Network Analyzer

Electrical and electronics engineers should understand that it is essential to recognize the pivotal role of filters across a spectrum of applications, especially in license-free bands used for industrial, scientific, and medical (ISM) applications inclusive of use in the internet of things (IoT). In wireless communication, these filters act as custodians, diligently channeling specific frequencies to avoid interference and maintain the coherence of devices such as Wi-Fi and Bluetooth-enabled systems.

Within the realm of healthcare, filters play a critical role in medical devices like MRI machines and wearable health monitors. By selectively permitting essential signals while blocking extraneous noise, these filters ensure the integrity of diagnostic and monitoring processes. In professional audio systems, bandpass filters contribute to the refinement of sound quality by allowing only targeted frequencies to reach the listener's ears, thereby enhancing the overall auditory experience.

Moreover, in the domain of radar technology, filters serve as indispensable components, facilitating precise signal processing for navigation and surveillance applications. The ubiquity of filters underscores their significance in optimizing the functionality and performance of diverse electronic systems, making them indispensable for budding electrical engineers navigating the intricacies of signal processing and frequency management.

Vector network analyzers (VNAs) are used to evaluate filter designs, both those that are tailor-made by an engineer to target a specific application as well as general off-the-shelf models manufactured in mass to address applications with common frequency-selective demands. This application note will leverage the latter, using a bandpass filter (Figure 1) found on a popular online shopping website with the intent for it to be used in a wide array of low device power (LDP) configurations that operate using the 70 cm band, specifically at or near 433 MHz.

Passband:	10M
Center frequency:	433M
Insertion loss:	<3 db
Input power:	<0.2w
Interface:	SMA - K
Weight:	Approx.6g/0.2oz
Package list:	1 x band-pass filter

Figure 1: General specifications for the generic 433 MHz bandpass filter.

The Bird BNA1000 Vector Network Analyzer is used to verify the return loss and insertion loss of the device. Further, a Smith Chart will be used to evaluate the complex impedance of the device and ensure a good match when added to the final system design.

Return Loss

Return loss – signified by the S11 parameter highlighted in **Figure 2** – measures how much power is reflected back into the source, indicating the efficiency of energy transfer. Because this attribute is a loss, we expect it to have a negative value, though it may also be shown in a positive absolute value format.Greater return loss values signify better impedance matching and reduced signal loss.

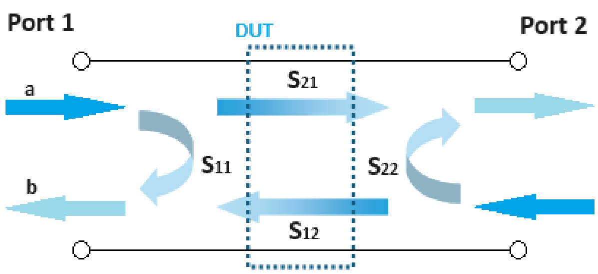

Figure 2: Return loss is a measure of the power reflected back to its source of origin.

A good design goal for a filter is to ensure that it achieves greater than 10 dB of loss at each of its frequency cutoff points. Because the filter specifications indicate a 10 MHz passband around a 433 MHz center frequency, we might expect measurements of -10 dB at the lower and upper cutoff frequencies of 428 MHz and 438 MHz, respectively, as seen in the ideal filter design simulation shown in **Figure 3**.

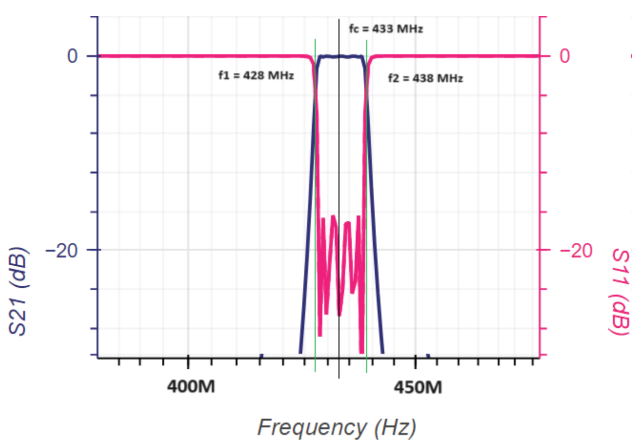

Figure 3: Filter design simulation identifying return loss (S11) of -10 dB at the cutoff frequencies (f1 & f2).

In our setup, we will look at a frequency spectrum that is twice the indicated pass band to achieve added visibility outside the intended operating region. To do so we start by setting the center frequency to 433 MHz then the span to 20 MHz. Additionally, to achieve 20 kHz resolution in the frequency sweep, we set the number of points to 1001.

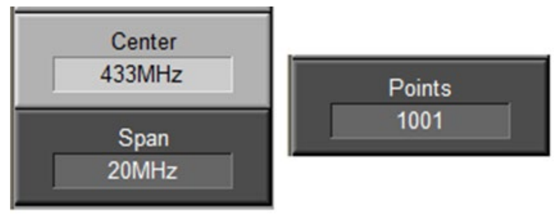

Figure 4: Use Stimulus->Center and Span options as well as Sweep Setup->Points to prepare for measurement calibration.

To properly verify that our bandpass filter aligns with performance expectations, we will first need to perform a 2-Port measurement calibration for VNA ports 1 and 2. Reasons for and how to perform measurement calibration fall outside the scope of this paper but can be better understood by referring to the supplementary application note “Ensuring Precision: The Importance of Vector Network Analyzer Calibration and How to Calibrate Your Bird Vector Network Analyzer”.

After the calibration is completed, our filter – the device under test (DUT) – is connected to the VNA such that Port 1 is mated to the RFin connector and Port 2 is mated to the RFout connector as in **Figure 5**.

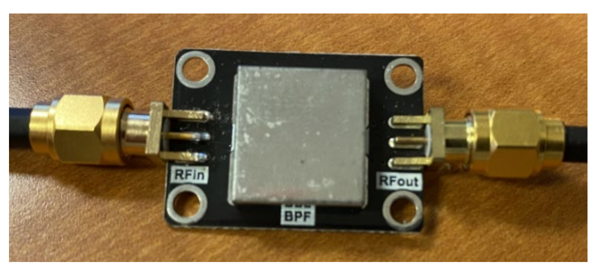

Figure 5: VNA ports 1 & 2 connected to RFin and RFout, respectively.

The default trace measurement is S11 on which we can add a marker and set its position to the 433 MHz point in the sweep to clearly identify the center frequency. Because we want to know the frequencies at the -10 dB points on either side of the center frequency, we can then add two additional markers and use the Marker Search function for each to accurately place them at our points of interest. Note that the frequencies for each of these markers (428.32045 MHz and 437.55168 MHz) closely align with our loss expectations with all frequencies between at -10 dB or more, indicating that our frequencies of interest will pass through the circuit with minimal disruption (Figure 6). There is the small band in between our two most recent markers, sitting at about 429.65 MHz with a width of around 1 MHz, that meanders above expectations and is noted by Marker 4 to which we can refer to in other measurements if it proves to be a problem spot.

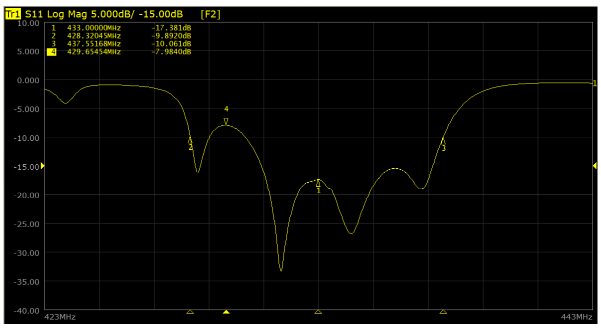

Figure 6: Reflection response and markers identifying the -10 dB points for the DUT.

Insertion Loss

Insertion loss – represented by the S21 parameter highlighted in **Figure 7** – quantifies the power loss introduced by the filter when a signal passes through it; it is an assessment on the impact of the filter based on the transmitted signal's amplitude.

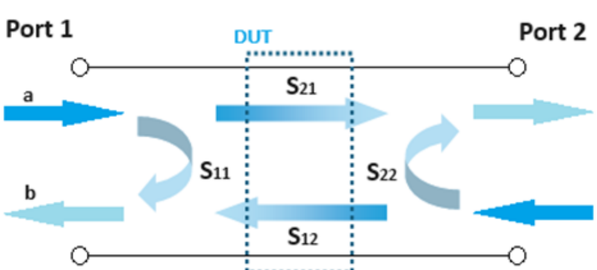

Figure 7: Transmission response (or insertion loss) is a measure of the power lost as the signal passes through the device.

Lower insertion loss values indicate better filter performance, as the filter minimally affects the signal amplitude.

It can be quite helpful to view insertion loss and return loss in the same channel view so that we can see how the responses align with one another. To do so, a second trace is allocated to the display area, using the S21 measurement setting and a log magnitude format then auto scaling to get the best view possible, the results of which are shown in **Figure 8**.

Figure 8: Transmission and reflection response traces overlaid on one another helping to show how the return loss and insertion loss properties relate to one another.

Recall from our specifications that we can expect <3 dB of insertion loss within the pass band of our DUT. With our S21 measurements in focus, we can see the measurements change for our defined markers based on their set frequency values. Marker 1 indicates -1.4590 dB and dragging this marker anywhere in between our other two markers should yield values <3 dB as well, though we find this is not the case near the left-hand side.

Based on the ideal bandpass filter design shown earlier, it would be reasonable to expect our S21 Markers 2 and 3 to have -3 dB measurements to coincide with the -10 dB return loss points measured in the previous section. While very close at Marker 3, our Marker 2 is reading -4.36 dB, potentially cutting short the frequency band we intend to use. It is no coincidence that the top of our pass band takes an early dip near Marker 4 where we proved less than ideal return loss.

Another way to better gauge the performance capability of our filter device is to enable the Bandwidth Search function of the VNA, in this case performing the search in reference to the maximum measurement point and to the -3 dB cutoff points with respect to the maximum. Note the solid blue upward-facing triangles in **Figure 9** to represent the calculated results.

Figure 9: The Bandpass Search function (found via Markers->Marker Search->Bandpass Search) can be used to compare real filter performance against calculated design values.

The Bandwidth Search function analyzes the measurements of the given trace and uses the information to display values representative of the selectivity of the filter, yielding more mathematically accurate representations of bandwidth, center frequency, upper and lower cutoff points, insertion loss and quality factor

Complex Impedance

The VNA can also help us understand some of the complex impedance attributes of our filter using the Smith Chart, showing how the nature of circuit changes in response to the frequency. To accomplish this, our layout can further be modified to:

- Add a third trace.
- Set its measurement to S11.
- Set its measurement format to Smith Chart, R+jX.
- And have just the Smith Chart displayed alone.

The outcome is shown in **Figure 10**.

Because the design is intended to operate in a 50-ohm system, a bandpass filter with a good match should have its impedance value near the center of the chart where the impedance is 50 Ω. Measurements above the horizontal center line of the chart are inductive in nature; those below are capacitive.

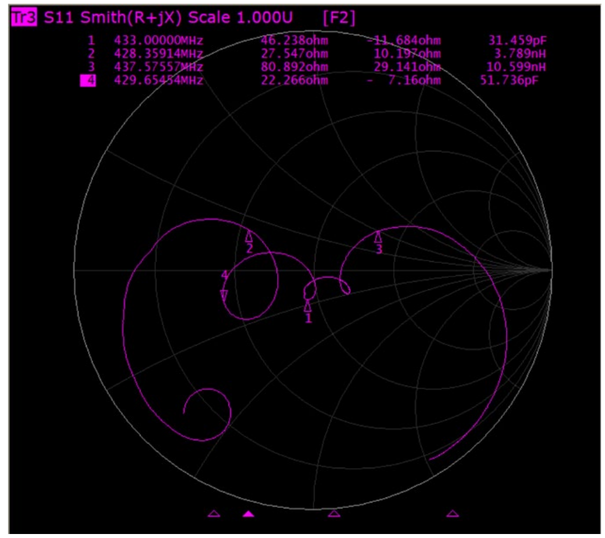

Figure 10: The Smith Chart helps us understand the complex impedance of our circuit design.

Marker 1 representing our center frequency is very near the 50 Ω point and, while though a bit capacitive, is showing signs of a good match. Markers 2 and 3 appear evenly separated from our center point and both inductively offset in the same direction.

What is more interesting is what happens to the impedance as the frequency moves outward from the center toward our cutoff frequencies. Note that there are two lobes that fall into the lower half of the chart, telling us that there is some capacitance in the system. The noteworthy part here is the left lobe around Marker 4 – to which we registered some suspicion earlier – shows significantly larger amount of capacitance. This may be telling us that a part change or trace re-routing in the high-pass portion of the filter could help balance the design and improve performance.

While we might believe a design improvement is in order, our Smith Chart observations may only apply to this single filter sample. To help determine if the frequency response is unique to just this device, we can preserve our active trace data (using Display->“Data->Memory”), insert a second sample in place of the first, then choose to view the Memory and Data traces together as shown in Figure 11. With the traces and markers showing a high degree of overlap, we can see how addressing the circuit design will result in optimized effectiveness.

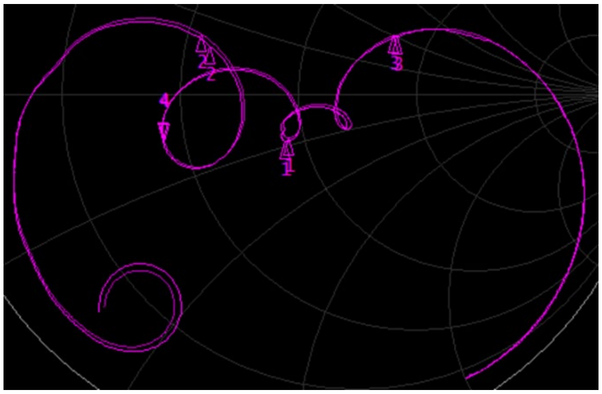

Figure 11: Repeating measurements on a second device sample can help confirm areas for improvement in the device design.

Conclusion

Engineers must grasp the importance of filters in different applications, particularly in wireless tech for IoT and ISM. Filters ensure smooth transmission of specific frequencies without interference in any number of frequency bands. The use of Vector Network Analyzers is crucial in evaluating bandpass filters, in this case for low-power setups at 433 MHz.

Return loss, signified by the S11 parameter, measures the efficiency of energy transfer, with greater loss values indicating better impedance matching. A good filter design aims for over 10 dB loss at each frequency cutoff point.

Insertion loss, represented by the S21 parameter, quantifies the power loss introduced by the filter, with lower loss values indicating better performance. Bandwidth Search function is employed to assess the filter's performance capability, providing mathematically accurate representations of bandwidth, center frequency, cutoff points, insertion loss, and quality factor.

The Smith Chart aids in evaluating the complex impedance of the filter, ensuring a good match in the final system, and also helping the user to understand capacitive and inductive properties of their design with respect to changes in frequency.

All evaluations should be preceded by a 2-port measurement calibration.

For more information about Vector Network Analyzers, please visit [https://birdrf.com.](https://birdrf.com)