AN11787

Low-Cost External Remote Keyless Entry (RKE) Low Noise Amplifier for 315 / 433 / 868 MHz Automotive Applications using the BFU520W RF Transistor

Rev. 1 — 22 March 2016 Application Note

Document information

Info	Content
Keywords	BFU520W, Remote Keyless Entry, RKE, Automotive, LNA
Abstract	This document provides circuit schematic, layout, BOM and typical evaluation board performance for a low-cost, wideband LNA covering 315, 433 & 868 MHz bands . Two LNA variants are presented; “Type 1” is set up to run from a fixed 5 volt supply (in-vehicle application) whereas the “Type 2” is modified so as to run from a single-cell battery as in a Keyfob.

Revision history

Rev	Date	Description
1	20160322	First publication

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1. Introduction

The **BFU520W** is an Automotive-Qualified (AEC-Q101) silicon RF Transistor for high-frequency, low-noise applications. BFU520W is one of 20 different types of RF transistor in NXP's new BFU5xxx family. Fabricated in a modern 8-inch process, these devices show exceptional device-to-device consistency and very high production yields. BFU5xxx devices are suitable for small signal to medium power RF applications up to 2 GHz, have a collector-emitter breakdown voltage BV_{CEO} of 12 volts, and are available in a wide variety of industry-standard surface-mount packages. All members of this transistor family are Automotive-Qualified per AEC-Q101. **Figure 1** below gives an overview of this family of devices, with the "Icc" row showing typical (not maximum permitted) operating currents for each type.

Package	Transistor Types				
Icc	5 mA	10 mA	20 mA	30 mA	150 mA
SOT323	BFU520W	BFU530W	BFU550W		
SOT23	BFU520A	BFU530A	BFU550A		
SOT143	BFU520	BFU530	BFU550		
SOT143X	BFU520X	BFU530X	BFU550X		
SOT143XR	BFU520XR	BFU530XR	BFU550XR		
SOT89				BFU580Q	BFU590Q
SOT223				BFU580G	BFU590G
SOT363	BFU520Y				

Fig 1. Overview of BFU5xxx family of RF Transistors

Key Benefits of BFU5xxx family:

- **Automotive-Qualified per AEC-Q101**
- High Gain, Low Noise Figure; suitable for applications up to 2 GHz
- Low cost / high performance-to-price ratio
- Five (5) different RF transistor chip types – covering low current, low-noise to higher current, medium power 'driver' applications
- Eight (8) different industry-standard package types with externally visible connections to facilitate visual inspection of solder joints
- Compliant to Directive 2002/95/EC, regarding Restriction of Hazardous Substances (RoHS) following NXP's RHF-2006 indicator D (dark green)

Key Benefits of BFU520W External RKE LNA described in this Applications Note:

- 3 – 5 dB improvement in RKE Receiver Sensitivity
- High Gain & Low Noise Figure with only ~ 3.5 mA current consumption
- Broad Bandwidth => same design used for 315, 433 & 868 MHz with no changes
- Very Low-cost implementation; no chip inductors (only resistors & capacitors)
- Unconditional Stability
- Easy-to-use, forgiving design, using only "E12" series component values
- Flexible – Gain, Linearity, etc. can be adjusted by changing values of externals

2. Automotive RKE application constraints, the 'range problem' and BFU520W LNA Design

Figure 2 shows frequency bands in use for Remote Keyless Entry applications, along with car & light truck production volumes for different regions as of 2015. RKE systems presently in use operate at 315, 433 or 868 MHz. Note, a half-wavelength at 315 MHz would be ~ 47.5 cm, & about 34.5 cm at 434 MHz. If we use a half-wave dipole as a starting point or reference for an RKE system antenna, one can imagine how large this antenna would be, especially for use in keyfobs. Bear in mind, antenna efficiency tends to degrade dramatically as we reduce antenna size below this half-wavelength value.

Region	Estimated Vehicle Production Volume (Millions), CY2015	RKE Frequency ('1-way' RKE)	Comments
EU	21	433 MHz	Limited 2-way RKE applications @ 868 MHz *
China	24	315 MHz	Limited 2-way RKE applications @ 868 MHz *
Japan	13	315 MHz	Very low permitted keyfob Tx output power
NAFTA	19	315 MHz	Limited 2-way RKE applications @ 868 MHz *
South America	3	315 MHz	Limited 2-way RKE applications @ 868 MHz *

Fig 2. World-wide frequency bands in use for RKE applications.

In automotive systems, the RKE receiver antenna is often placed in a non-ideal location for radio signal propagation - in the vehicle's dashboard or other position dictated by cost and practical considerations. Such non-ideal locations increase path loss & reduce RKE system range. Furthermore, the antennas used are typically printed on a PC board, or constructed with wire or stamped metal, with lowest possible cost and poor efficiency. Lastly, these antennas are often 'electrically short' or smaller than a half-wavelength, in addition to being bent and folded into strange shapes, due to size constraints. All of these compromises further degrade antenna efficiency. See **Figure 3** for an example.

Fig 3. Example automotive RKE receiver block which would be placed in a vehicle. Note low-cost wire antenna, which is bent & folded to fit the available space. This implementation is far less efficient than our classic λ/2 dipole used as a reference. Size and cost limitations adversely affect antenna efficiency, reducing RKE system range.

It must be emphasized, that the above described compromises made to RKE antenna placement and implementation all tend to reduce the radio link margin or range of the RKE system. In newer, emerging 2-Way RKE systems, the small 'keyfob' held by the vehicle operator also must have an RKE receiver / transceiver installed, and keyfob antennas are even smaller and less efficient, being only a small fraction of a wavelength in size. **Meanwhile, automotive manufacturers & their customers demand ever increasing range (and thus better radio link margin), with the RKE system being expected to work at ranges of 30 to 100 meters or more**.

Despite improvements in Noise Figure (and receiver sensitivity) of CMOS RKE integrated circuits themselves, the range of the RKE system is often less than desired, given all the aforementioned compromises made for the sake of cost-reduction & practicality. The Automotive RKE system designer is faced with a challenge, of how to increase RKE system range in a cost-effective way. **Figure 4** gives a list of the most common options available to increase RKE radio link margin, along with limitations of each. **The last option – addition of an external Low Noise Amplifier (LNA) stage – is usually the best option, and this application note will describe such an external LNA made with NXP's Automotive-Qualified BFU520W RF Transistor.**

Option	Comment
Improve antenna efficiency	Limited by space & cost
Increase transmitter output power	Limited or constrained by battery life & government regulations
Improve RKE receiver IC noise figure / sensitivity	Limited by CMOS process
Add an external Low Noise Amplifier (LNA) between antenna and RKE IC	Most cost-effective option with minimal increase in current consumption

Fig 4. Options and constraints for increasing RKE system range

Friis' formula in **Figure 5**, describes how overall receiver noise figure of a multi-stage system is calculated. Reducing overall or 'cascaded receiver noise figure' will increase the range of the radio link. Per Friis' formula, placing a low noise gain stage with Noise Factor F_1 and Gain G_1 in front of the RKE receiver block will reduce the noise figure contribution of subsequent stages by the reciprocal of the first stage's gain value. If the Noise Figure of the external LNA in front of the receiver chain is sufficiently low, and LNA gain sufficiently high, a significant improvement in overall receiver sensitivity and range can be achieved. The trade-off, or price paid for using this option, is some reduction in the ability of the receiver chain to handle large signals or 'jammers' due to the additional gain added, as well as some increase in power consumption due to the addition of the external LNA stage. The general rule-of-thumb for receiver design is, for the first LNA stage, use as low of a noise figure LNA as reasonably possible, with just enough gain such that this first stage 'dominates' or 'sets' the overall receiver noise figure. Avoiding use of excessive gain will minimize the adverse impact on large signal handling ability for the receiver. There are various software tools available for making these calculations and trade-offs, ranging from simple spreadsheets to more sophisticated system simulation software tools.

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + ... + \frac{F_n - 1}{G_1 G_2 ... G_{n-1}}$$

Fig 5. Friis' formula for calculation of overall or 'cascaded' noise figure of a receiver.

In testing with Automotive RKE Receiver and Transceiver IC's, it has been shown that overall receiver sensitivity can be improved by 3 to 5 dB by using the BFU520W external LNA described in this Applications Note.

2.1 BFU520W External Automotive RKE LNA Design Targets

The 'ideal' LNA should have some or all of the following characteristics:

i) The active device should be AEC-Q101 qualified

ii) Gain 13 - 15 dB with Noise Figure < 2 dB

iii) Ability to adjust / increase or decrease Gain

iv) Low-cost

v) Operate at 5 volts (in-vehicle) or over 1.9 – 3.6 volts (from keyfob battery)

vi) Low current consumption

vii) Adjustable operating current to optimize linearity, Gain, etc.

viii) Unconditional Stability ("K" > 1 and $B_1 > 0$; or $\mu_1 > 1.0$)

ix) Wide Bandwidth to cover 315, 434 & 868 MHz bands with same design; broadband matching will also make LNA serve as a good termination for adjacent circuit blocks (filters, switches, antennas, etc.)

x) Simple, flexible forgiving design insensitive to PC board layout variation

Using the BFU520W RF Transistor in a resistive-feedback configuration achieves the above listed goals. The LNA Gain may be increased or decreased somewhat by varying the amount of negative feedback used – simply by changing the value of the RF feedback resistor. Gain and Linearity may also be increased by increasing LNA operating current via changing the value of the bias resistor(s). This process is described in a later section of this document. Note, **no chip inductors are used** to further reduce cost – only resistors and capacitors are required.

Two variants of this basic LNA design are described in subsequent sections. Please refer to **Figure 6.** The "Type 1" refers to the in-vehicle external LNA, which runs from a 5 volt regulated power supply; the "Type 2" has its bias resistor values changed to be able to operate off of a keyfob battery – i.e. 3.6 V when the keyfob's battery is fully charged, down to 1.9 V when the battery is near the end of its life.

The schematic diagram and Bill Of Material (BOM) for each of the two LNA variants are shown in later sections.

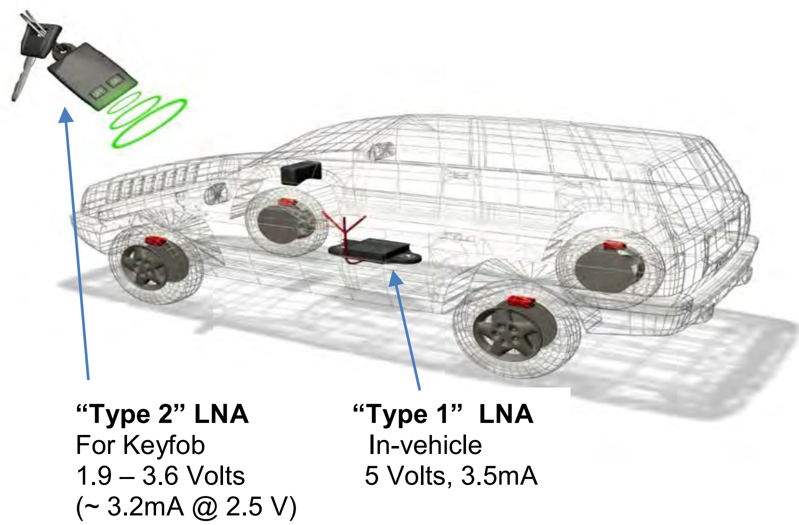

Fig 6. "Type 1" and "Type 2" BFU520W External LNA Variants

2.2 PC Board Details, both LNA Types

The same printed circuit board is used for both Type 1 and Type 2 LNA's. **Figure 7** gives a cross-sectional diagram of the circuit board, and **Figures 8** and **9** provide photos of the assembled board. Standard, low-cost FR4 PC board material is used along with '0402' case size passives. Note, for the circuits shown in this Applications Note, only 'E12' series component values are used. 50 ohm microstrip traces are used for the input and output transmission lines. Via holes are 0.2 mm / 0.008 inch diameter drill size, before metal plating of through-holes. The total board thickness of ~ 0.060 inch / 1.65 mm makes the circuit board stiff enough to reduce flexing or bending, helping to prevent damage or cracking to components mounted to the PCB.

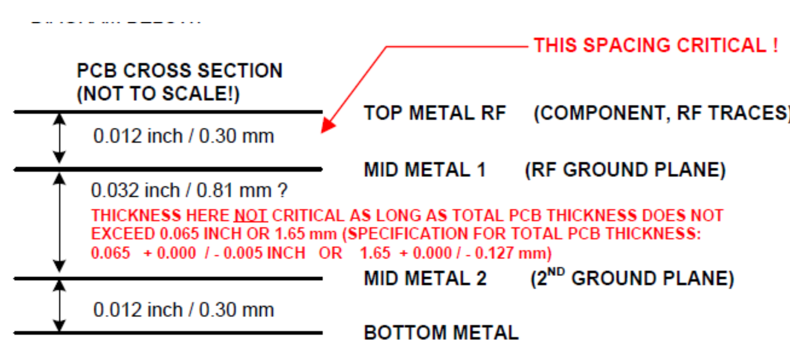

Fig 7. Cross-sectional diagram of BFU520W External RKE LNA Board

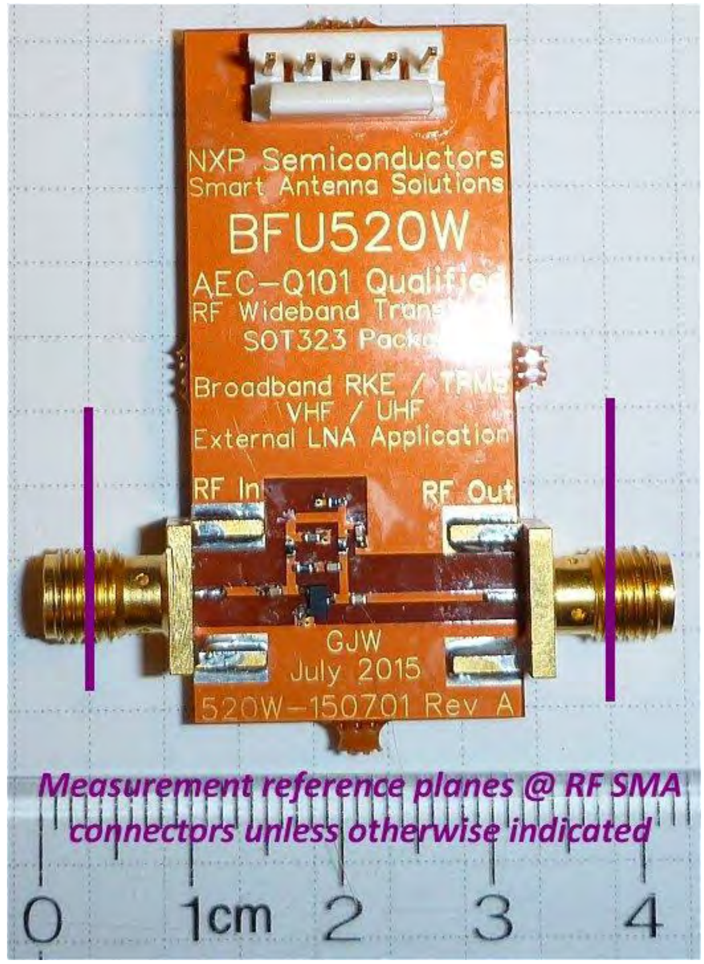

Fig 8. Photo of assembled BFU520W LNA PC board. Measurement reference planes for data shown in this document are as shown at RF connectors unless otherwise indicated.

Fig 9. Close-in photo of PC board with '0402' case-size resistors and capacitors used.

3. Typical Application Board Test Results, “Type 1” LNA (5 Volts, 3.5mA)

This section presents results of a typical “Type 1” BFU520W LNA, designed for placement in a vehicle and running from a fixed 5 volt power supply. Measurement results are summarized in **Figure 10**. The Schematic Diagram and Bill of Material (BOM) are given in **Figures 11** and **12**, respectively. Parts placement is shown in **Figure 13**.

(T=25 °C, network analyzer source power ≈ -30 dBm, V_{CC} = 5.0 V, V_{CE} = 3.2 V, I_C=3.5 mA, Z_S=Z_L=50 Ω)

Frequency MHz	dB[s11]^2	dB[s21]^2	dB[s12]^2	dB[s22]^2	* NF dB	IIP$_3$ dBm	OIP$_3$ dBm	IP$_{1dB}$ dBm	OP$_{1dB}$ DBm
315	-10.2	15.2	-21.5	-11.5	1.5	- 13.2	+2.0	-21.9	-6.7
434	-10.5	14.6	-21.3	-11.4	1.5	-13.4	+1.2	-21.7	-7.1
868	-11.7	11.9	-20.1	-10.3	1.5	---	---	---	---
915	-11.8	11.6	-19.9	-10.2	1.4	---	---	---	---

*** does not extract PCB loss**

If PCB and RF connector loss (at input) were extracted, noise figure would be ~ 0.1 dB lower

Fig 10. Summary of measurement data for “Type 1” BFU520W LNA.

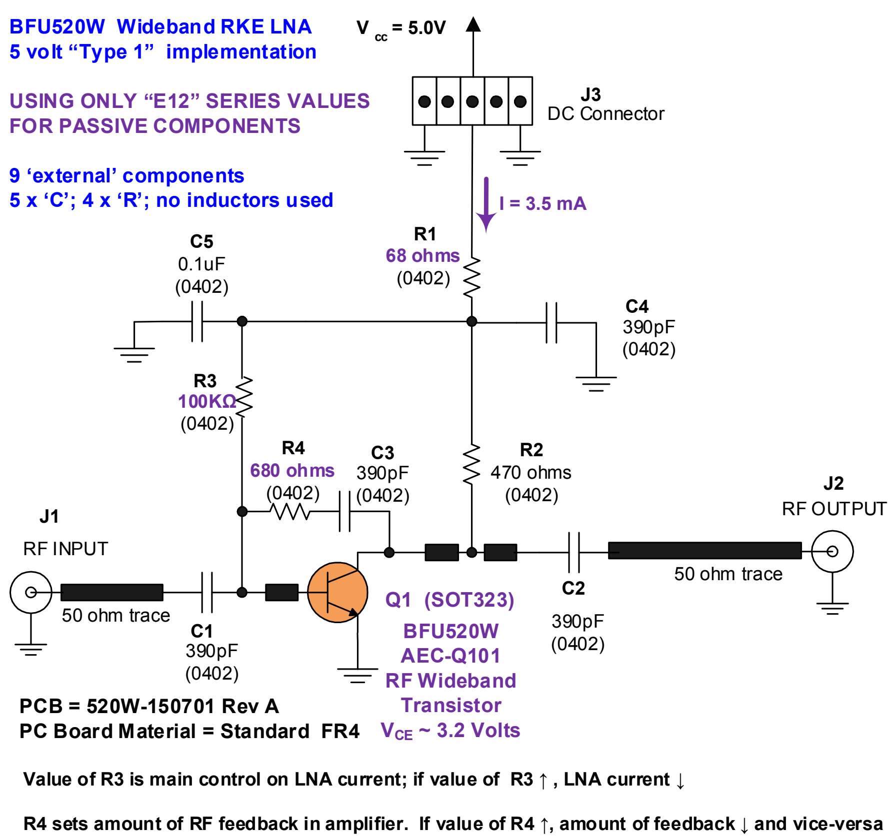

Fig 11. Schematic Diagram, “Type 1” BFU520W LNA.

Reference	Value	Function / Description
Q1	-	Active Device NXP BFU520W RF wideband Transistor, AEC-Q101 Qualified, SOT323 package
C1, C2	390 pF	Input & Output DC blocks
C3	390 pF	DC block for RF feedback path (collector-to-base)
C4	390 pF	Power supply decoupling, collector
C5	0.1 µF	Low-frequency decoupling
R1	68 Ω	DC bias resistor; provides some DC negative feedback to DC operating point to compensate for changes in Q1's h_{FE} over temperature, etc.
R2	470 Ω	"RF Choke" for collector (RF output) of Q1; lower cost than an inductor Trade-off: 'softer' Gain Compression curve, some loss of linearity
R3	100 kΩ	DC bias feed to base of Q1; primary resistor for setting Q1 collector current; adjust I_C by varying this value
R4	680 Ω	RF negative feedback to amp; when value of R4 ↓, amount of feedback is increased & vice-versa. Can decrease LNA gain by making value of R4↓. But, more feedback makes Noise Figure ↑

Fig 12. Bill Of Material (BOM, for Type 1 BFU520W RKE LNA (5 volt, 3.2mA variant).

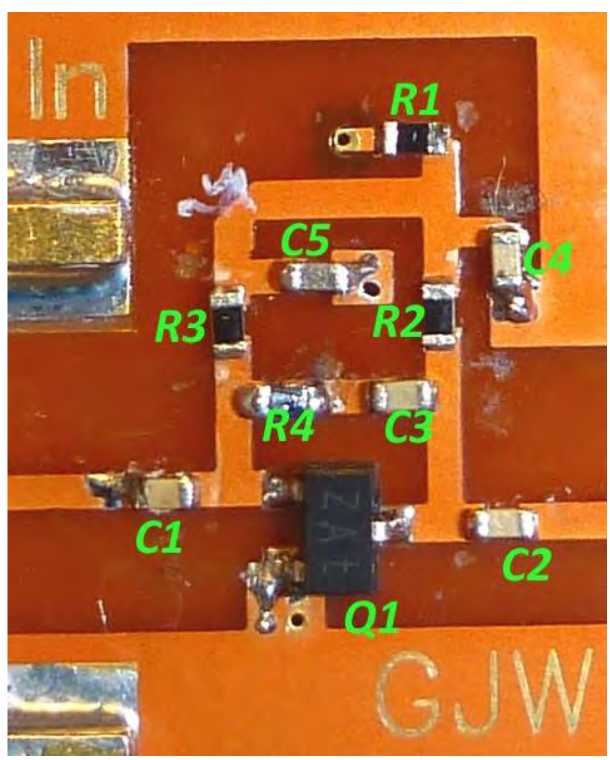

Fig 13. Parts placement on PC Board for both "Type 1" and "Type 2" BFU520W LNAs.

3.1 S-Parameters, Stability Factor and Noise Figure, "Type 1" LNA

Figures 14 – 17 show broadband (25 MHz – 6 GHz) S-parameters for "Type 1" (5 volt, 3.5mA) BFU520W RKE LNA, taken at T=25ºC. **Figure 18** shows Stability Factor μ_1, which verifies Unconditional Stability over 25 MHz – 6 GHz. Lastly, LNA Noise Figure is given in **Figure 19**.

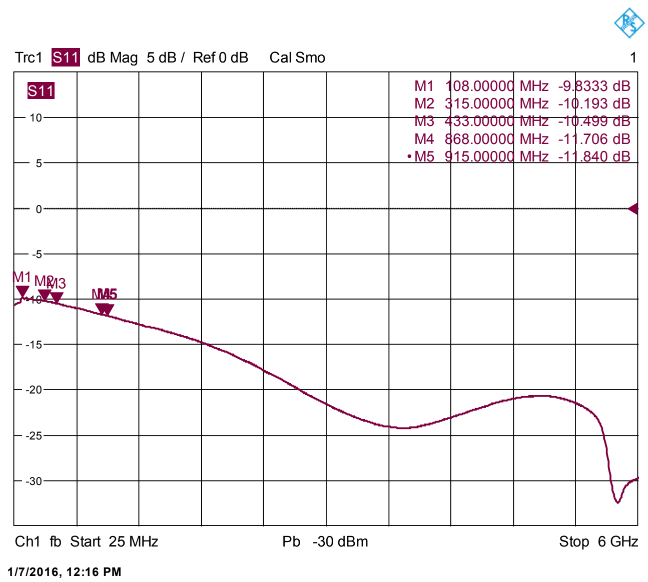

Fig. 14 BFU520W "Type 1" RKE LNA, Input Return Loss. Note broadband / wideband matching.

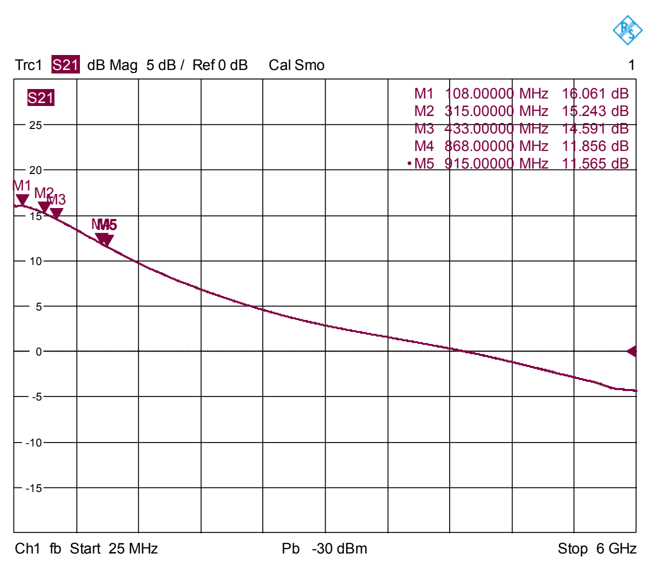

Fig. 15 BFU520W "Type 1" RKE LNA, Forward Gain

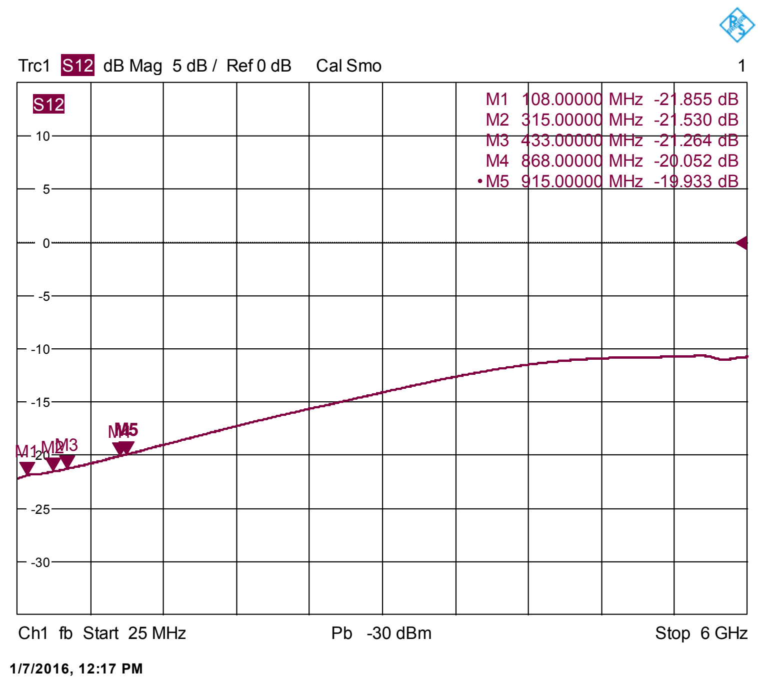

Fig 16. BFU520W "Type 1" RKE LNA, Reverse Isolation

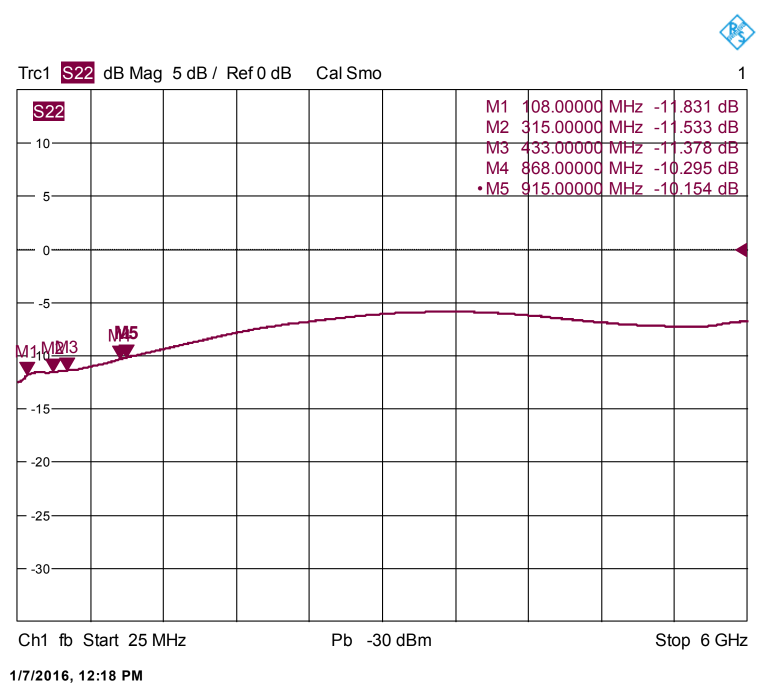

Fig 17. BFU520W "Type 1" RKE LNA, Output Return Loss. Note broadband / wideband matching.

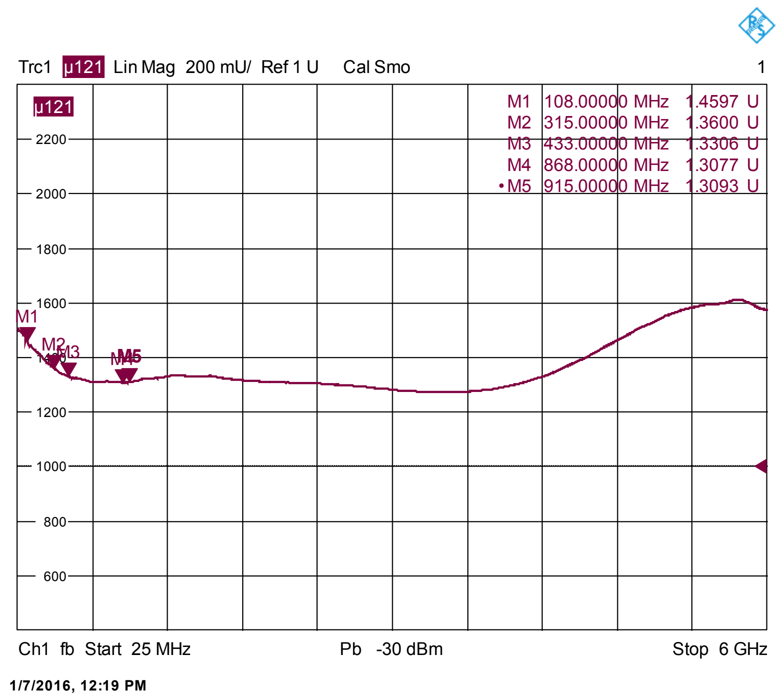

Fig 18. BFU520W "Type 1" RKE LNA, Stability Factor "μ_1". $\mu_1 > 1.0$ is a necessary and sufficient condition for Unconditional Stability. LNA is Unconditionally Stable over 25 MHz – 6 GHz.

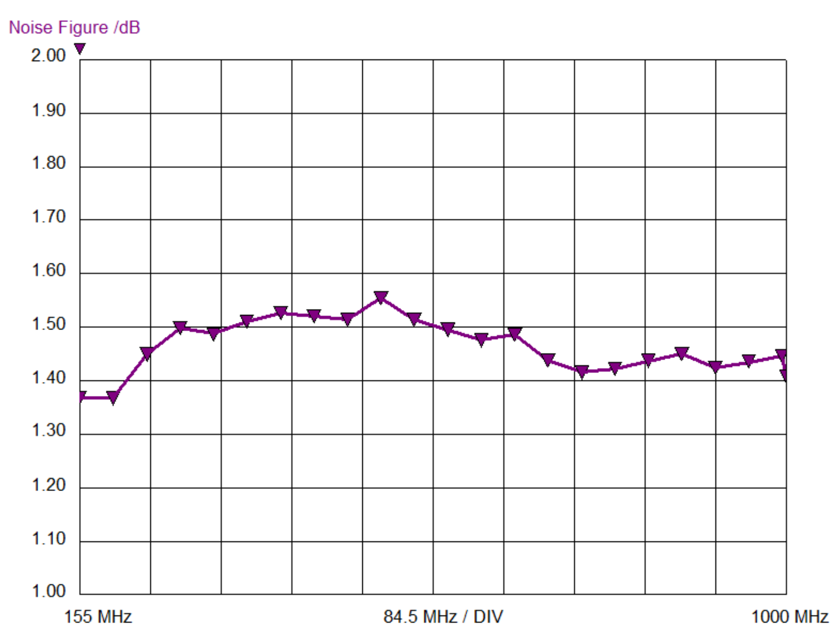

Fig 19. BFU520W "Type 1" RKE LNA, Noise Figure for T = 25ºC.

4. Typical Application Board Results, “Type 2” LNA for Keyfob Applications (1.9 – 3.6 Volts, 3.2 mA @ 2.5 V)

This section shows results of a typical “Type 2” BFU520W RKE LNA, used for placement in a Keyfob, running from a coin cell battery. Intended voltage range is ~ 3.6 volts when battery is fully charged, down to ~ 1.9 volts at end of battery life. Data for T=25ºC, for both 315 & 433 MHz is summarized at 1.9, 2.5, 3.0 and 3.6 volts in Figure 20. Schematic Diagram & BOM are given in Figures 21 & 22. Note, only resistor value changes are needed moving from Type 1 => Type 2 configuration.

Frequency (MHz)	Supply Voltage V_{CC} (Volts)	LNA Current (mA)	LNA V_{CE} (Volts)	dB[s11]^2	dB[s21]^2	dB[s22]^2	Noise Figure (dB) *	Input P_{1dB} (dBm)	Output P_{1dB} (dBm)	Comments
315	1.9	2.09	1.24	-6.5	11.7	-9.6	1.8	--	---	Gain, NF significantly degraded @ 1.9V / 2.1mA
	2.5	3.21	1.49	-9.4	14.2	-12.7	1.6	--	---	“Nominal” operation point
	3.0	4.14	1.70	-11.8	15.4	-15.0	1.5	--	---	
	3.6	5.25	1.94	-14.8	16.5	-18.4	1.5	--	---	Good Gain if battery charged
433	1.9	2.09	1.24	-6.7	11.2	-9.8	1.8	-22.8	-12.6	Gain, NF significantly degraded @ 1.9V / 2.1mA
	2.5	3.21	1.49	-9.7	13.5	-12.6	1.6	-21.5	-9.0	“Nominal” operation point
	3.0	4.14	1.70	-11.9	14.7	-15.1	1.5	-20.4	-6.7	
	3.6	5.25	1.94	-14.5	15.6	-17.9	1.5	-19.2	-4.6	Good Gain if battery charged

Fig 20. Summary of data for “Type 2” BFU520W RKE LNA, for T=25ºC, at 1.9, 2.5, 3.0 & 3.6 Volts.

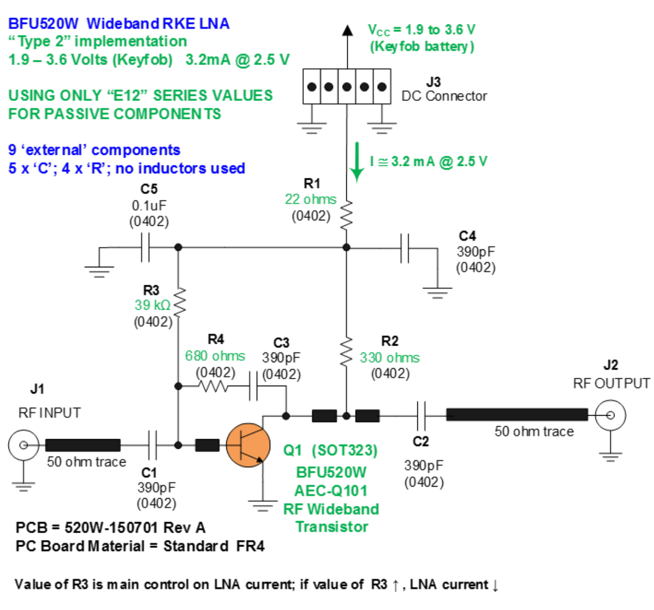

Fig 21. Schematic Diagram, “Type 2” BFU520W RKE LNA, intended for keyfob.

Reference	Value	Description / Function
Q1	-	Active Device NXP BFU520W RF wideband Transistor, AEC-Q101 Qualified, SOT323 package
C1, C2, C3, C4	390 pF	Input & Output DC blocks (C1, C2); DC Block for RF Feedback path (C3); power supply decoupling (C4)
C5	0.1 µF	Low-frequency decoupling
R1	22 Ω	DC bias resistor; provides some DC negative feedback to DC operating point to compensate for changes in Q1's h_{FE} over temperature, etc.
R2	330 Ω	"RF Choke" for collector (RF output) of Q1; lower cost than an inductor Trade-off: 'softer' Gain Compression curve, some loss of linearity
R3	39kΩ	DC bias feed to base of Q1; primary resistor for setting Q1 collector current; adjust I_C by varying this value
R4	680 Ω	RF negative feedback to amp; when value of R4 ↓, amount of feedback is increased & vice-versa. Can decrease LNA gain by making value of R4↓. But, more feedback makes Noise Figure ↑

Fig 22. Bill Of Material (BOM) for "Type 2" BFU520W RKE LNA intended for Keyfob.

4.1 Supply current, S-Parameters, Stability Factor and Noise Figure over battery voltage (~ 3.6 volts down to ~ 1.9 volts) "Type 2" LNA

Data for the "Type 2" Keyfob-type BFU520W RKE LNA is presented in this section, showing how the LNA operating current and RF parameters vary over battery voltage at T=25ºC. The main conclusions are as follows:

1) **LNA current** varies from ~ 2.1 – 5.3mA over 1.9 – 3.6 volt battery voltage range
2) **Gain** stays between 14 – 17 dB at 315 / 433 MHz for 2.5 – 3.6 volts; Gain drops to 11 – 12 dB at 1.9 volts
3) **Noise Figure** remains fairly constant between 2.5 – 3.6 volts, with ~ 0.3 dB degradation at 1.9 volts
4) **Unconditional Stability** is maintained across entire 1.9 – 3.6 volt range
5) **Impedance Match** degrades as supply voltage (and thus LNA current) decreases, with the most severe change occurring from 2.5 => 1.9 volts

Figure 23 shows LNA current variation over battery voltage range. **Figure 24** shows LNA Input Return Loss vs voltage, and **Figure 25, 26 & 27** show Gain, Reverse Isolation, and Output Return Loss vs. voltage, respectively. The stability factor μ_1 of the amplifier at each of the four voltages tested is shown in **Figures 28 – 31**. Noise Figure at each test voltage is shown in **Figures 32 – 35**.

Supply Voltage V_{CC} (Volts)	LNA Current (mA)	BFU520W V_{CE} (Volts)	Comment
1.9	2.09	1.24	
2.5	3.21	1.49	Nominal, ‘set point’
3.0	4.14	1.70	
3.6	5.25	1.94	

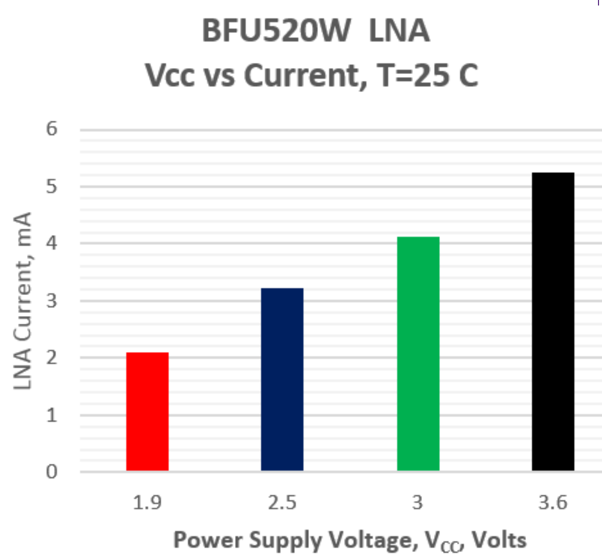

Fig 23. Variation in LNA current & collector-emitter voltage vs. battery voltage for a “Type 2” BFU520W RKE Keyfob LNA.

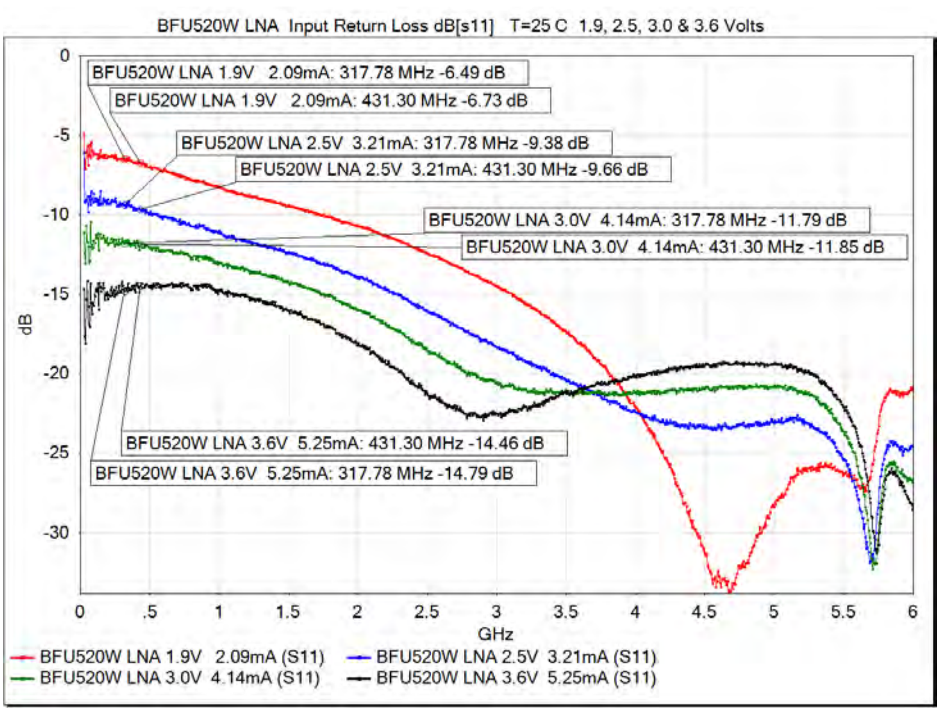

Fig 24. Input Return Loss vs Battery Voltage for a “Type 2” BFU520W RKE LNA, for 25 MHz – 6 GHz. Note, input match degrades as voltage decreases.

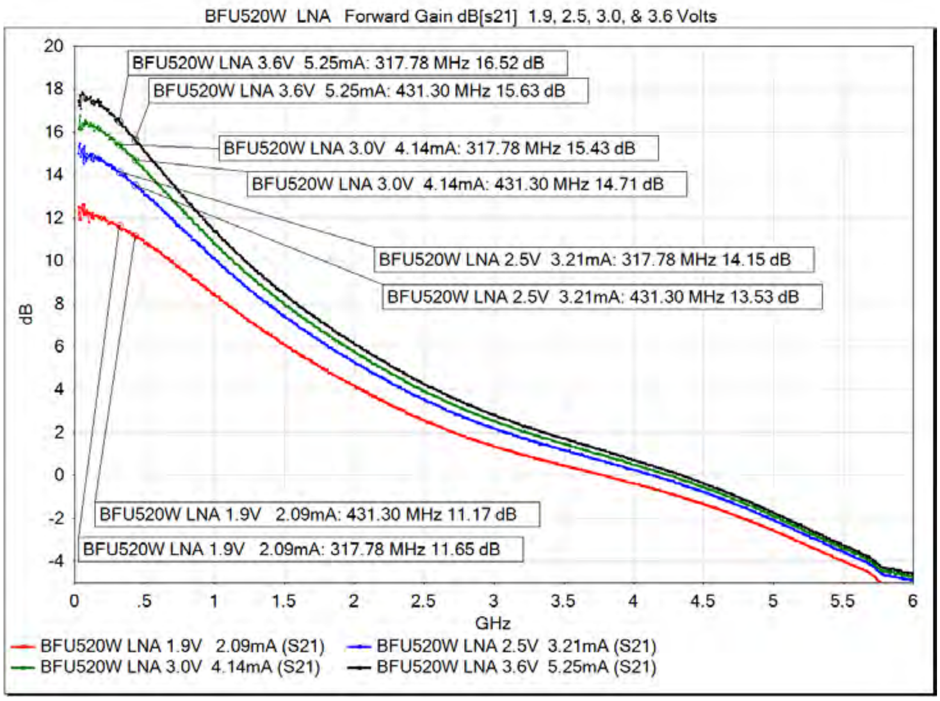

Fig 25. Gain vs Battery Voltage for a "Type 2" BFU520W RKE LNA, for 25 MHz – 6 GHz. We see a total gain variation of ~ -4.5 dB at 315 or 433 MHz as voltage decreases from 3.6 V down to 1.9V.

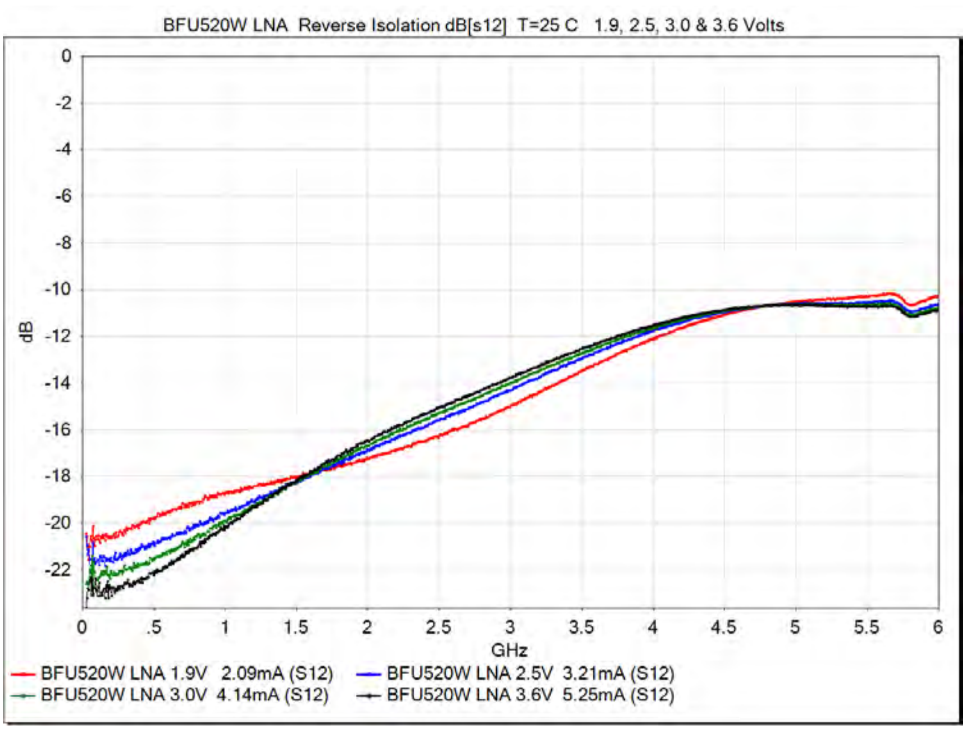

Fig 26. Reverse Isolation vs Battery Voltage for a "Type 2" BFU520W RKE LNA, for 25 MHz – 6 GHz.

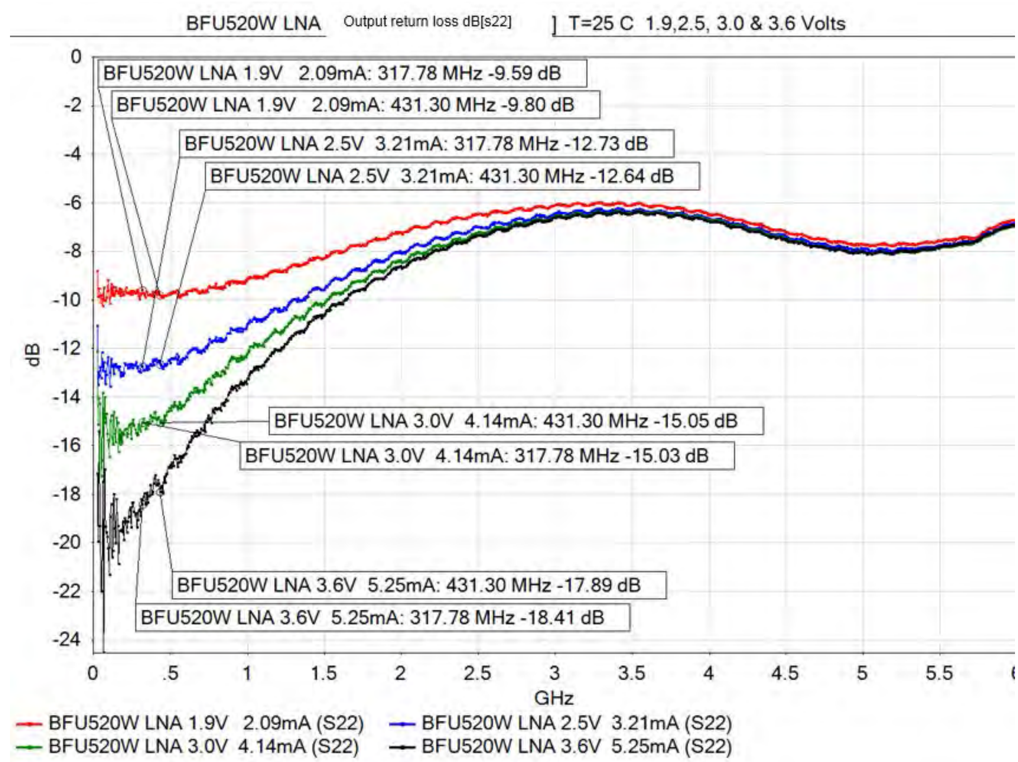

Fig 27. Output Return Loss vs Battery Voltage for a “Type 2” BFU520W RKE LNA, for 25 MHz – 6 GHz.

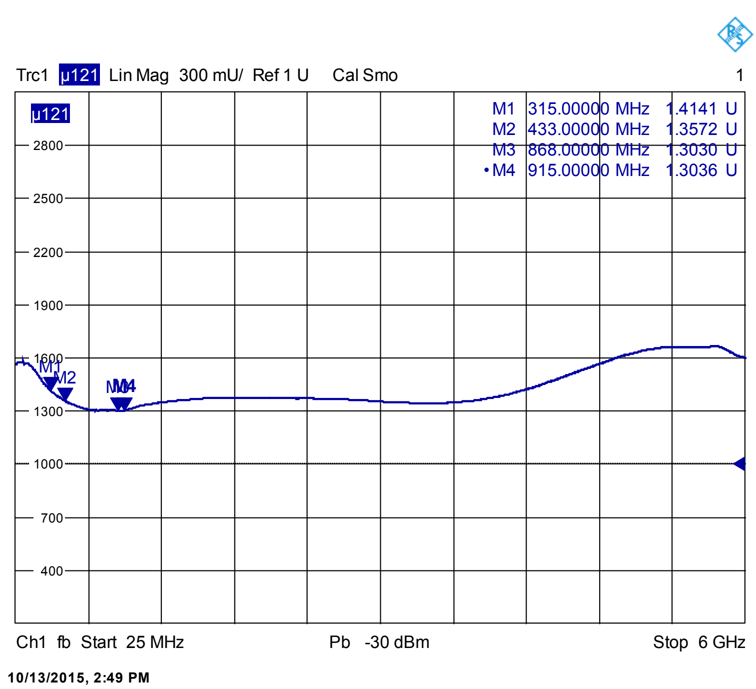

Fig 28. Stability factor μ_1 at 1.9 volts, “Type 2” BFU520W RKE LNA, for 25 MHz – 6 GHz.

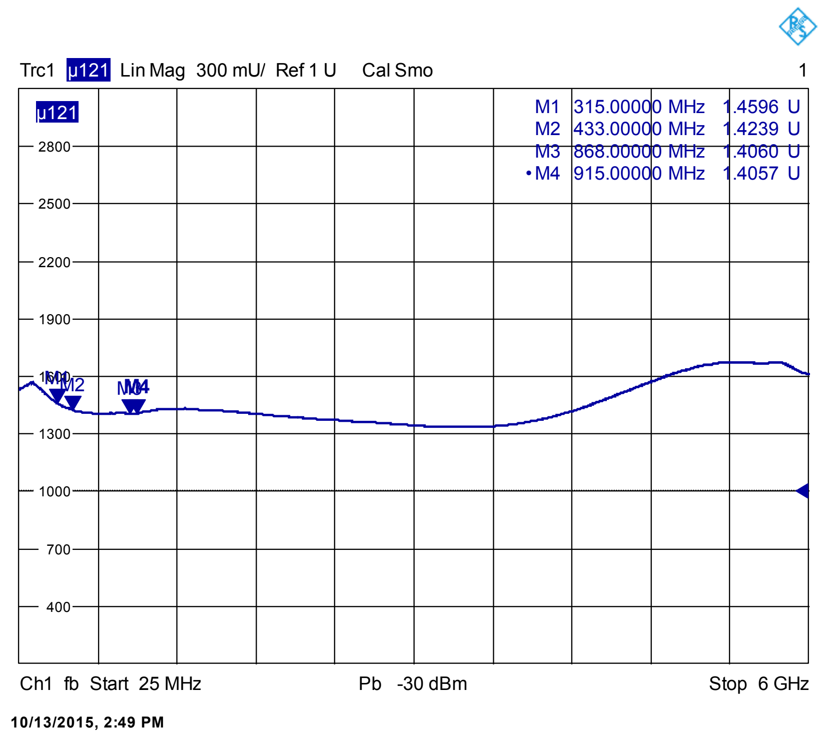

Fig 29. Stability factor µ1 at 2.5 volts, "Type 2" BFU520W RKE LNA, for 25 MHz – 6 GHz.

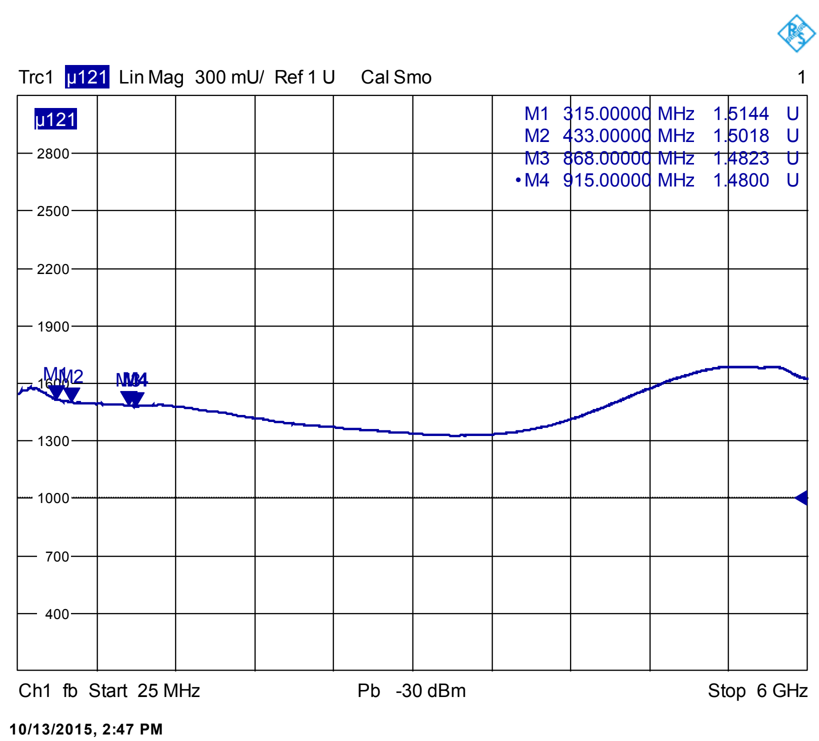

Fig 30. Stability factor µ1 at 3.0 volts, "Type 2" BFU520W RKE LNA, for 25 MHz – 6 GHz.

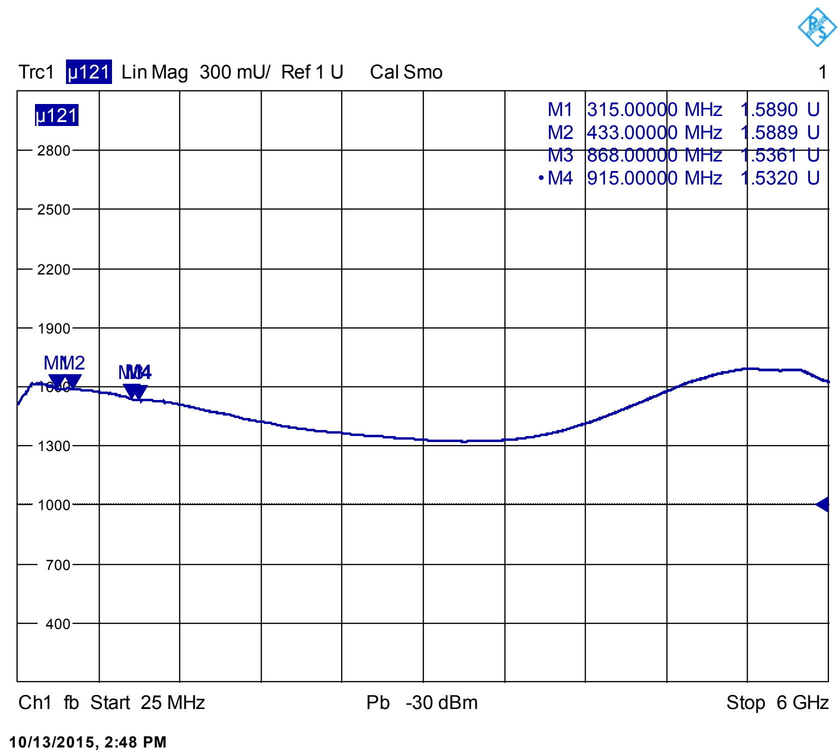

Fig 31. Stability factor μ_1 at 3.6 volts, “Type 2” BFU520W RKE LNA, for 25 MHz – 6 GHz.

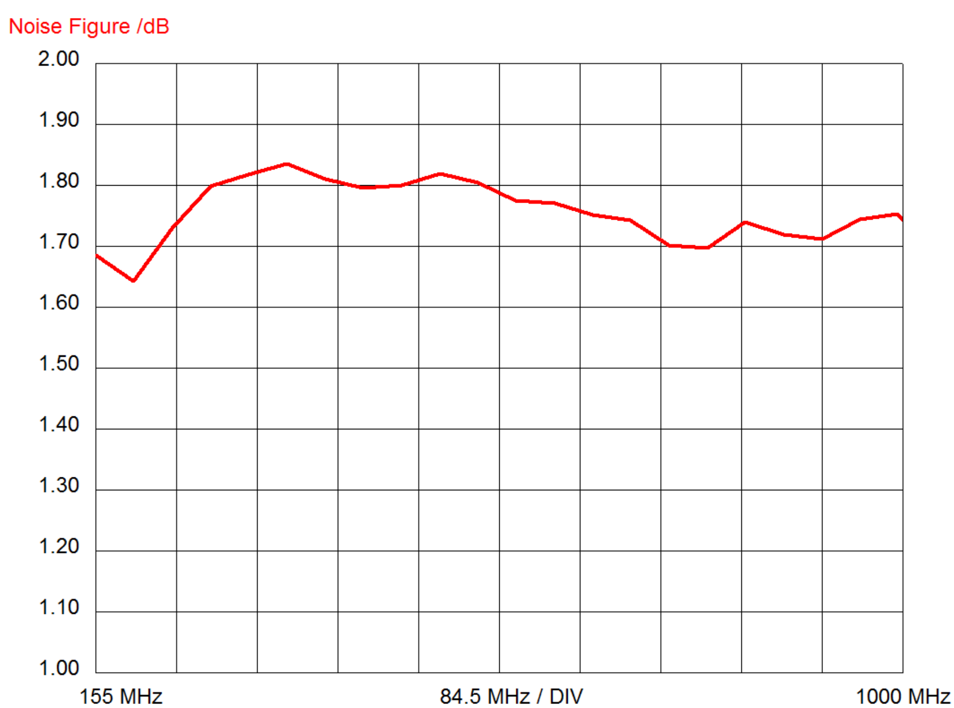

Fig 32. Noise Figure at 1.9 volts, “Type 2” BFU520W RKE LNA

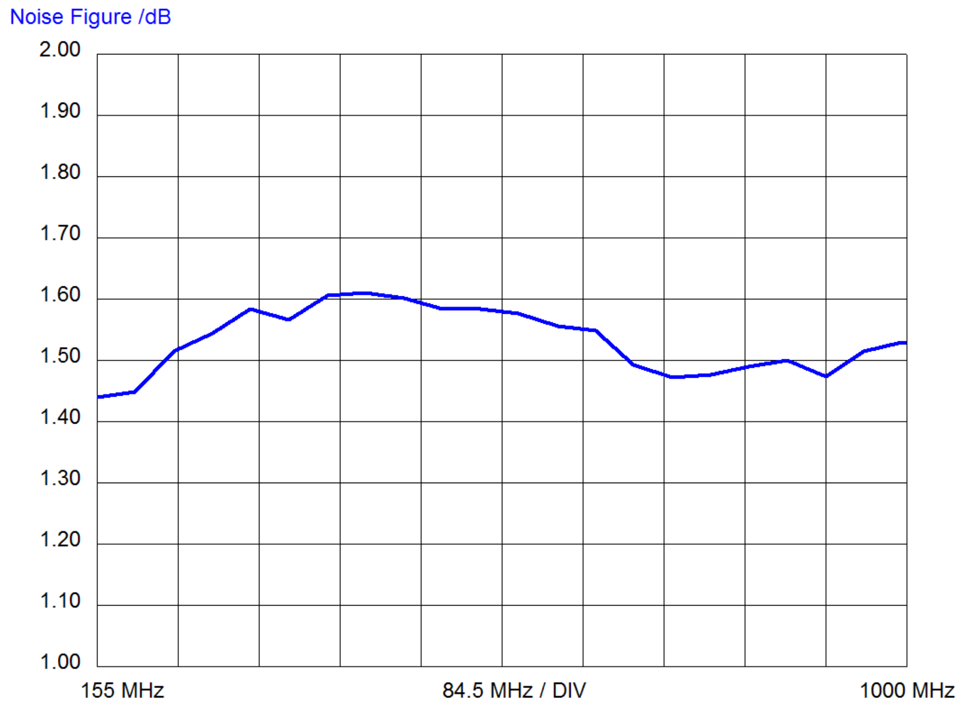

Fig 33. Noise Figure at 2.5 volts, “Type 2” BFU520W RKE LNA

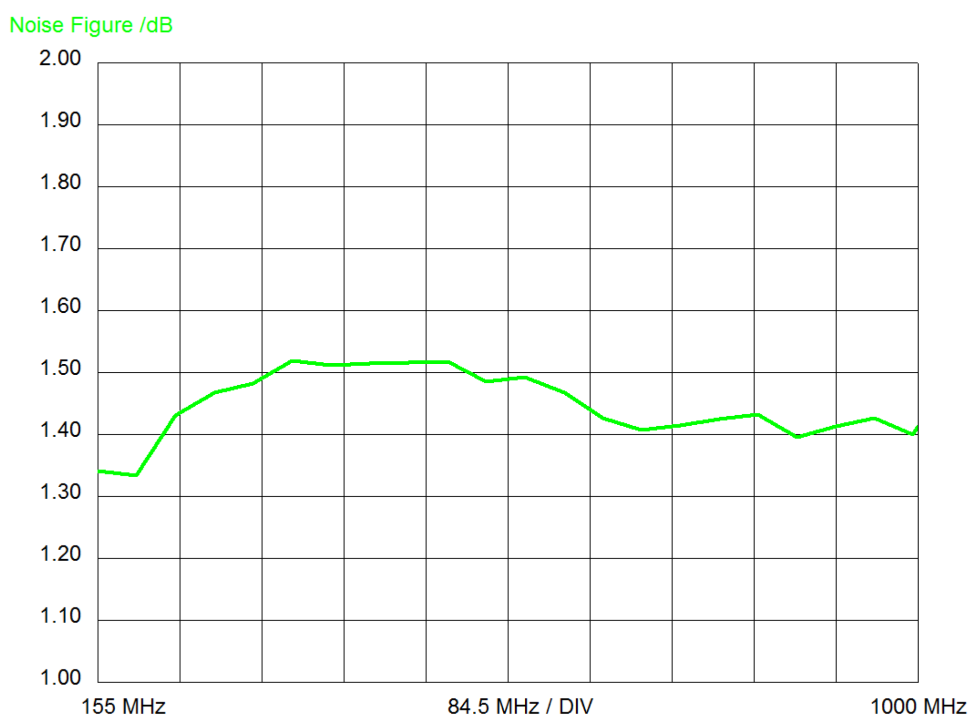

Fig 34. Noise Figure at 3.0 volts, “Type 2” BFU520W RKE LNA

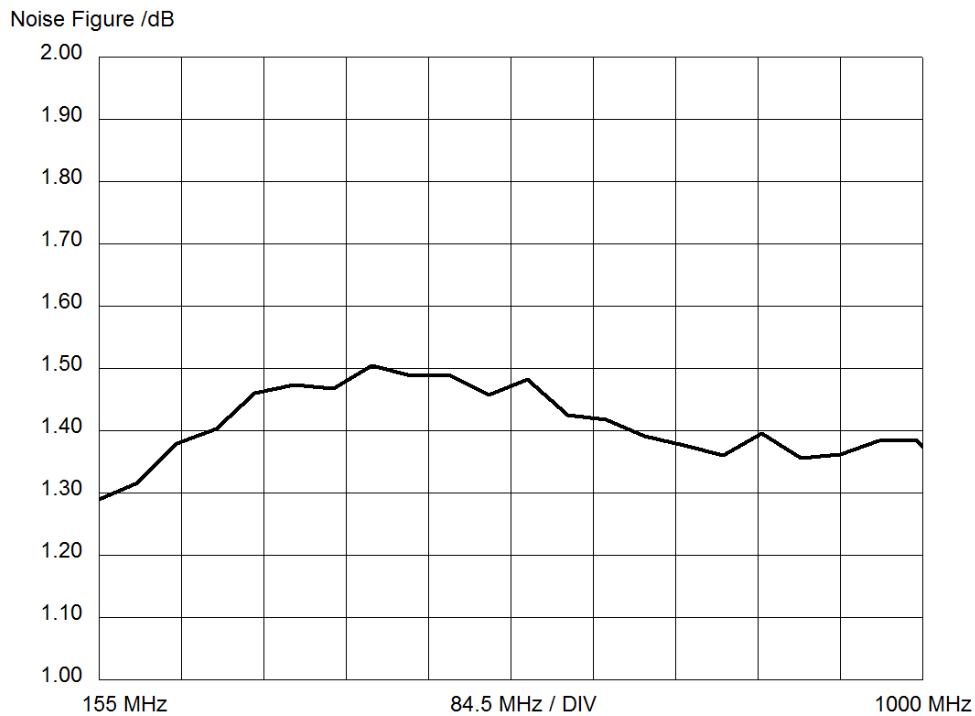

Fig 35. Noise Figure at 3.6 volts, “Type 2” BFU520W RKE LNA

5. Information on BFU520W RKE LNA Customer Evaluation Kits

There are two (2) types of fully populated and tested BFU520W RKE LNA Customer Evaluation Kits available, one for each of the “Type 1” and “Type 2” demos described in this applications note. Each kit has a PC board and some extra BFU520W device samples in it. Please reference the information below when placing an order for a Customer Evaluation Kit through your NXP Sales Representative.

Name	Description	Artf	OM-	12NC
BFU520W-RKE1	**Type 1** In-vehicle (5 volt, 3.5mA)	157556	**OM17022**	12NC 934070272598
BFU520W-RKE2	**Type 2** For Keyfob (1.9 – 3.6 volts, 3.2mA @ 2.5 Volts)	162023	**OM17023**	12NC 934070273598

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7. List of figures

8. Contents

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