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SDARS-GNSS LNA THAT CAN COEXIST WITH CELLULAR

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Abstract

The 2320-2345MHz band is licensed to Sirius XM for broadcasting Satellite Digital Audio Radio Service (SDARS). Out-of-band (OOB) transmissions can disrupt SDARS reception through blocking. The blocker can either emanate from nearby vehicles, or can be self-inflicted because the vehicular SDARS aerial often share a common radome with cellular aerials. Among cellular bands, the Wireless Communications Service's (WCS) 2305-2320MHz and 2345-2360MHz are the most disruptive because they sandwich SDARS without any guard band. As the SDARS aerial is connected to the receiver through 15-20 feet of coaxial cable, an outboard low noise amplifier (LNA) is necessary to overcome cable loss. Due to stringent noise requirement, the LNAs are predominantly discrete designs which necessitate many components and large printed circuit boards (PCB), but vehicular aesthetic and aerodynamic demand small and unobtrusive radomes. When reception of global navigation satellite system (GNSS) is also required, the additional aerial and LNA further increase the space pressure. A dual-band aerial can eliminate one aerial, but still requires a diplexer to interface with two LNAs. Narrowband receivers conventionally employ a band-select filter before the LNA, i.e. pre-filter, as the primary defence against OOB blockers. However, the insertion loss of a miniature microwave filter is incompatible with the SDARS LNA's noise requirement. The pre-filter will also prevent GNSS reception. In order to reject WCS blockers, the filter must possess narrow fractional bandwidth (~1%) and steep skirts. Most prior arts utilize either surface acoustic wave (SAW) or dielectric filters because they have the required selectivity but they add cost and PCB space. To reduce component count, we integrated RF amplifiers, active biasing, impedance matching and band-filtering into a 5×5mm^2 multi-chip on board (MCOB) module. To save on a separate GNSS LNA, the module is dual-band capable; hence eliminating the need for a diplexer between aerial and LNA. The conflicting requirements for low noise and blocking immunity are satisfied by relocating the filter to mid-LNA and distributing the gain optimally. An SDARS LNA's blocking tolerance is reported for the first time. In conclusion, this design achieves previously unattainable miniaturization and blocking performance.

Keywords:

SDARS GNSS Low Noise Amplifier, Wireless Communications Service Blocker Tolerant, Cellular Coexistence, Miniaturize

1. INTRODUCTION

The 2320 to 2345MHz band is licensed to Sirius XM in US and Canada for broadcasting Satellite Digital Audio Radio Service (SDARS) compact disc quality audio to paying subscribers [1] [2]. Although cellular transmissions are on different frequencies, they can disrupt SDARS reception through blocking (Fig.1). The blocker can either emanate from nearby vehicles, or can be self-inflicted because the vehicular SDARS aerial often share a common radome with cellular aerials [3] [4] [5] where the unwanted coupling is typically less than -20dB [6]. Considering the SDARS satellites are ~40,000km away, this is an extreme example of the near-far problem. Although all existing cellular bands can block SDARS to some degree, the proposed Wireless Communications Service (WCS) in the 2305-2320MHz and 2345-2360MHz bands is even more potentially disruptive because the two bands sandwich SDARS without any guard band [7] [8].

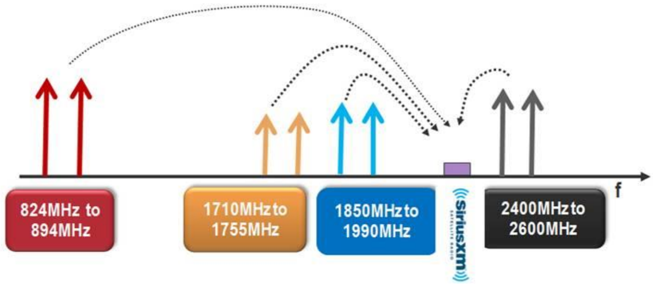

Fig.1. The SDARS band allocated to Sirius XM is surrounded by cellular services. Nearby cellular transmissions can impair the weak-signal SDARS reception.

Because the roof-top radome is connected to the dash-mounted SDARS receiver through 15-20 feet of coaxial cable [9], an outboard low noise amplifier (LNA) is necessary to overcome cable loss [10]. Due to SDARS' low noise requirement, the majority of LNAs are discrete designs. The LNA's discrete implementation necessitates many components and a large printed circuit board (PCB) area, but vehicular aesthetic and aerodynamic demand a small and unobtrusive radome. When reception of global navigation satellite system (GNSS) is also required, the additional aerial and LNA further increase the space pressure. A dual-band SDARS/GNSS aerial [11] [12] can free up space by eliminating the separate GNSS aerial, but the advantage is negated by the requirement for a diplexer to interface with two LNAs.

Narrowband receivers conventionally employ a band-select filter before the LNA (pre-filter) as the primary defence against out-of-band (OOB) blockers [13]-[15]. Since there is no gain before the pre-filter, its insertion loss will directly add to the overall noise figure (NF). SDARS' space constraint necessitates a miniature microwave filter in this slot, but such filter has substantial insertion loss [16]. Moreover, the SDARS pre-filter will prevent GNSS reception. If the band-select filter is relocated to the middle of the LNA chain, i.e. an inter-stage filter, the NF will degrade less than pre-filtering. On the flip side, without the pre-filter, the first RF stage is exposed to OOB blockers. Hence, sensitivity and blocking immunity are conflicting requirements in the SDARS LNA.

In order to attenuate the adjacent WCS band, the filter must possess narrow fractional bandwidth (~1%) and steep skirts. Because surface acoustic wave (SAW) and dielectric filters have the required selectivity, they are incorporated by most of the prior arts, but these off-chip filters add substantial size and cost.

Blocking impairs reception by raising NF via either one or both of the following mechanisms: (a) the LNA's gain compresses and this allows pre-existing noise to dominate, or (b) the low frequency noise is up-converted by mixing with the interference [17]. Surprisingly, none of the SDARS prior arts publish this critical parameter.

To reduce SDARS LNA's cost and size, we integrated RF amplifiers, active biasing, impedance matching and band-select filtering into a multi-chip on board (MCOB) module measuring 5.0×5.0×0.95mm^2. To save on a separate GNSS LNA, we designed the LNA to serve both bands. Since the dual-band LNA can directly interface with the SDARS-GNSS aerial without a diplexer, additional saving in cost, space and insertion loss are achieved. To resolve the conflicting requirements for low noise and high blocking immunity, we adopted inter-stage filtering and distributed the LNA gain to mitigate blocking. To redress the knowledge gap on blocking tolerance, this parameter is reported for the first time for an SDARS LNA. The motivation for this work is to create a module and a reference design for adoption by manufacturers. This article summarizes the design considerations and key performances

2. MATERIALS AND METHODS

2.1 GENERAL

The SDARS front end is characterized by a low aerial gain of ≤4dBi [18] [19], and a high cable loss, typically -10dB. To compensate for the two deficiencies, this design targets ~35dB of gain. If this design is realized with 0.25µm enhancement-mode pseudomorphic high electron mobility transistors (ePHEMT) [20] [21], three amplifier stages (Q1-Q3) will be required to meet the target gain (Fig.2).

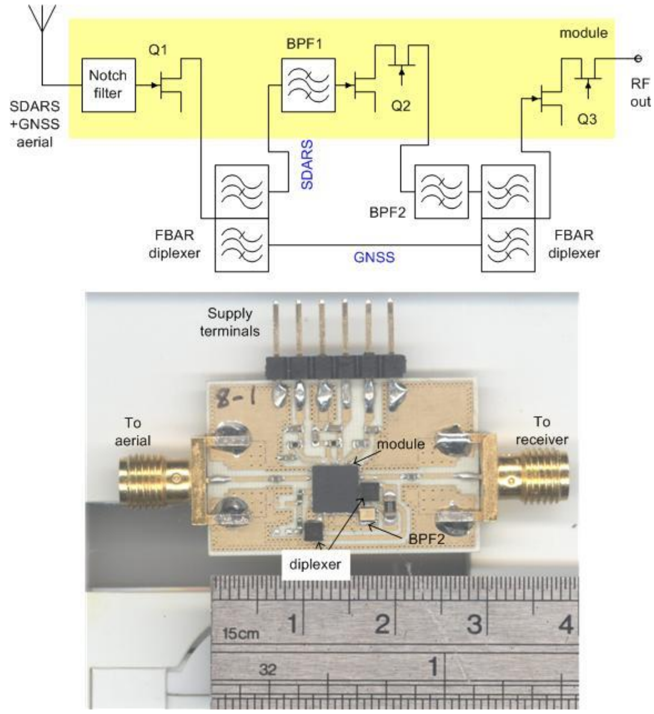

Fig.2. The combined SDARS and GNSS low noise amplifier occupies a small PCB area and requires few external components

Table.1. Target SDARS gain/loss and noise figure for each stage

	G (dB)	NF (dB)
Connector and input trace	-0.1	0.1
Q1 amp.	10.1	0.8
diplexer	-0.8	0.8
BPF1 filter	-1	1
Q2 amp.	13.3	0.84
BPF2 filter	-3	3
diplexer	-0.8	0.8
Q3 amp.	16.4	0.83
Total	34.1	1.2

GNSS requires less gain (~30dB) from the LNA than SDARS. To lower the gain in the GNSS band, the second stage Q2 is bypassed using a pair of miniature duplexers; i.e. the GNSS signal is amplified by Q1 and Q3 only. FBAR duplexers [22] [23] are selected because of their combination of low insertion loss and compactness; their 2×2mm^2 size belies their RF performances: ~1.1dB loss at SDARS and ~0.9dB at GNSS [24]. The duplexer's GNSS arm has a -3dB bandwidth of 1555-1618MHz which provides selectivity for GNSS reception.

2.2 ACHIEVING BLOCKER TOLERANCE WITHOUT PRE-FILTERING

The second and third LNA stages, Q2-3, are protected from OOB blockers by the inter-stage filters, BPF1-2. In contrast, the first stage Q1 has no protection from blockers because of the decision to forgo pre-filtering. As a result, Q1 becomes the bottleneck to the overall blocking performance. To mitigate Q1's blocking vulnerability, the stage gain is deliberately kept low (~10dB) because this has the effect of raising the input gain compression point (IP1dB). It is possible to improve blocking immunity by raising the bias current, but this option is limited by SDARS' 100mA maximum current specification for the LNA. For additional rejection at cellular frequencies, Q1's input network incorporates simple LC notch filters at 860MHz and 1960MHz.

Since Q2 and Q3 are preceded by filters, they can have higher gains without the risk of blocking. Their higher gains are achieved by using cascode stages as opposed to Q1's common-source topology.

While low-to-high gain distribution between Q1-3 improves blocking tolerance, it sacrifices NF because the first stage gain is insufficient to overcome the subsequent stages' noise contribution. As a result, the overall noise figure is ~0.3dB higher than the first stage's (Table.1). However, this amount of NF degradation is significantly less than what the pre-filter would have incurred.

2.3 FILTERING FOR COEXISTENCE WITH WCS

As discussed previously, the filters' positions in the LNA chain represent a compromise between blocker rejection and noise performances. The 1st inter-stage filter BPF1 is internally connected between Q1 and Q2. Due to Q1's low gain, BPF1 must have low insertion loss in order to preserve the overall noise figure. Additionally, BPF1 must be compact enough for integration. Film Bulk Acoustic Resonator (FBAR) technology

[25]-[27] is selected for BPF1 because it has a low insertion loss (~1dB) that belies its tininess [28]. On the downside, the filter bandwidth is about three times the SDARS channel bandwidth; i.e. 75MHz vs. 25MHz (Fig.3). While this filter is sufficient to reject existing cellular services, it is ineffective against the planned adjacent WCS channels.

To reject WCS, a second filter (BPF2) with the required narrow bandwidth (25MHz at the -3dB points) is connected externally between Q2 and Q3. BPF2 is Bulk Acoustic Wave (BAW) filter [29] which has more loss than the first (3dB vs. 1dB), but this is an acceptable compromise because the position between Q2 and Q3 has a lesser impact on the overall noise figure.

Another benefit of using two filters instead of one is improved stopband suppression. When BPF2 is evaluated alone, its upper stopband has a -40dB flyback (Fig.3). But when the two filters are combined, the flyback improves to better than -60dB.

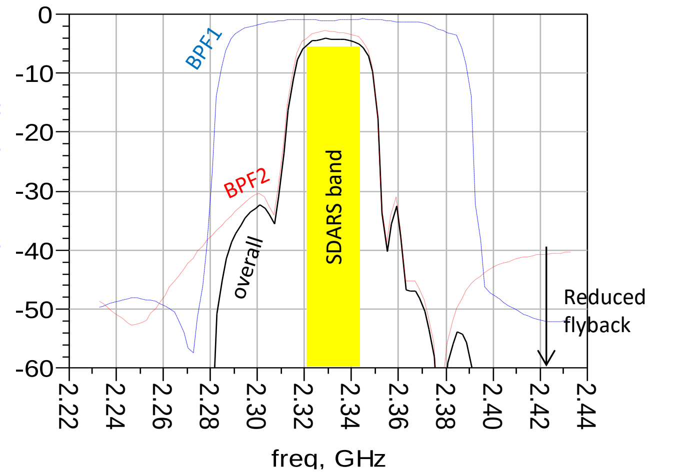

Fig.3. Simulated frequency responses of each filter (BPF1 and 2) individually and when combined together. The cascaded response is steep enough to reject the adjacent WCS bands

2.4 PROTOTYPE FABRICATION AND TESTING

The components are assembled on a 10 mil Rogers RO4350 [30] printed circuit board (PCB). All signal and power traces are on one side and a ground-plane on the other side. A FR4 backing layer is attached to the ground plane for strength and to increase the stack height to the standard 1.6mm.

The LNA is designed to operate from a single 5V supply. The current consumption of each amplifier can be individually adjusted via external resistances. This allows power consumption to be traded-off for blocking immunity and vice-versa. In this prototype, Q1-3's quiescent currents are set to 47mA, 12mA and 37mA, respectively because it optimizes blocking tolerance while ensuring the total current satisfies SDARS's 100mA limit.

3. RESULTS

3.1 FUNCTION INTEGRATION AND MINIATURIZATION

This design is remarkable for being the smallest SDARS LNA ever reported and for integrating the most functions. Its PCB size is half of the nearest competitor even though the latter lacked GNSS capability (Table.2). When compared to the sole GNSS-capable competitor [32], this work is three times smaller (570mm^2 vs. 1798mm^2).

Table.2. The proposed work integrates more functions and is more compact than competing SDARS LNAs

	Integrated Functions					
Reference	**Active Bias**	**Matching**	**Filter**	**GNSS**	**Components**	**PCB area (mm)**
Marino [31]	No	No	No	No	?	?
Sharawi [32]	No	No	No	Y	?	1798
Hong [33]	No	No	No	No	14	1750
Schwing Schakl [34]	No	No	No	No	?	?
NXP [35]	No	No	No	No	28	1200
Skywork [36]	Y	No	No	No	34	?
This work	Y	Y	Y	Y	14	570

This section first reports the in-band performances and then the out-of-band performances.

3.2 SDARS WEAK-SIGNAL PERFORMANCES

The LNA is capable of better than 1.2dB NF and more than 33.8dB gain in the SDARS band spanning 2320-2345MHz. The results include PCB and connector losses. Specifically, the loss between the RF connector and module's input is ~0.1dB. The average noise figure of 4 samples is 1.1dB at midband (Fig.4). As previously discussed, the overall noise figure is significantly higher than Q1's noise figure because Q1's gain is not sufficient to overcome the combined losses of the first diplexer and BPF1.

The samples' average gain is 34.4dB. The pass-band ripple is less than 1dB; this being a function of the filter Q. The bandwidth at the -3dB points is ~30MHz.

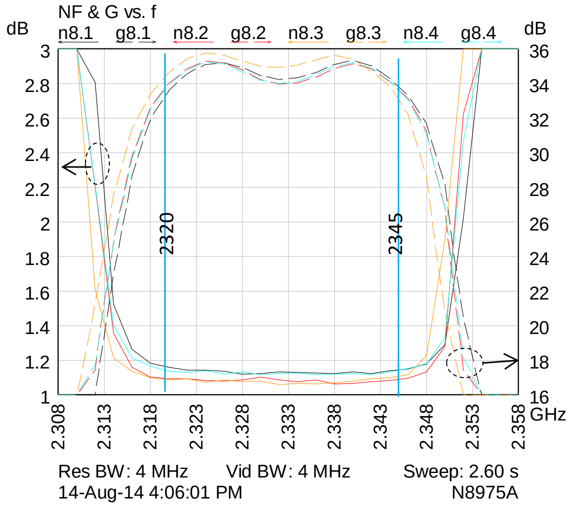

Fig.4. SDARS gain and noise figure vs. frequency ($n = 4$)

3.3 GNSS WEAK-SIGNAL PERFORMANCES

This design is capable of better than 0.9dB noise figure and more than 30dB gain in the GNSS band. Within GNSS's 1565-1606MHz band limits, the average noise figure of three samples is 0.83dB, while the noise figure varies less than 0.1dB (Fig.5). The in-band gain averages 30.3dB, while the gain ripple is less than 0.8dB. The gain passband has a -3dB bandwidth of ~50MHz.

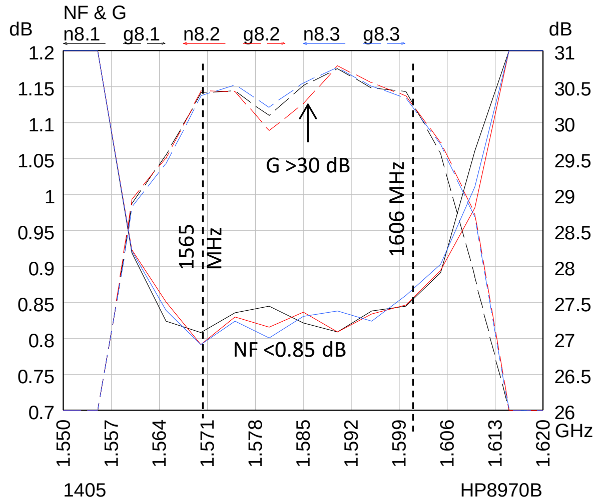

Fig.5. GNSS noise figure and gain vs. frequency (*n* = 3)

3.4 SDARS AND CELLULAR COEXISTENCE

This SDARS LNA can withstand out-of-band (OOB) signal up to 0dBm without NF degradation. Using the measurement setup described in [37], the NF at the middle of the SDARS band (2333MHz) is measured while different blocker frequencies are injected into the LNA input. Of the blocker frequencies evaluated, 2410MHz is the most harmful (Fig.6) because of its proximity to the SDARS band. Conversely, 890MHz and 1990MHz blockers have the least effect on the NF because they are attenuated by Q1's notch filters. To our knowledge, this is the first time an SDARS LNA's blocking performance is reported.

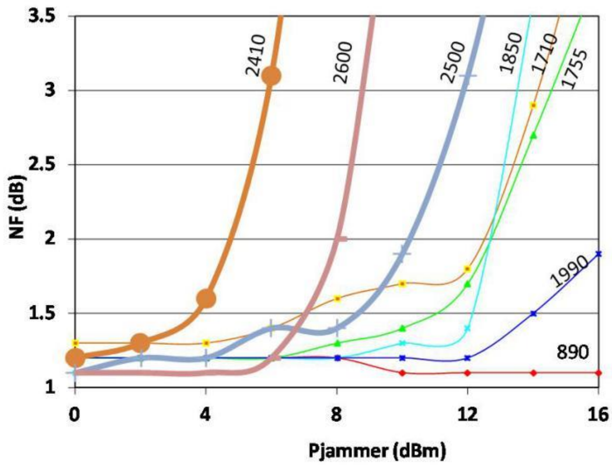

Fig.6. SDARS noise figure (NF) vs. blocker power (Pjammer) as a function of blocker frequency. The noise figure is not affected by any blocker weaker than 0dBm

Many blocker mitigation schemes have been proposed to replace the traditional pre-filtering, but this work is arguably the most effective. The NF impairment (ΔNF) when subjected to a 0dBm blocker is commonly used to compare blocking tolerance between various designs. Since SDARS prior arts do not report their blocking performances, this work has to be compared with designs from the cellular domain. This work's worst case NF impairment is 0.1dB only; in comparison, the nearest competitor is impaired by 2.2dB (Table.3). Another advantage of this work is that it contains far fewer components than the competing techniques.

Table.3. In a survey of blocker mitigation techniques, this work has the lowest noise figure impairment (ΔNF)

Reference	**Frequency (GHz)**	**NF (dB)**	**NF at 0dBm blocker (dB)**	**ΔNF (dB)**
Noise-cancelling LNA and voltage sampling mixer [37]	2	3.2	13	9.8
Switched-capacitor N-path filter [38]	1.9	3.1	11.4	8.3
SAW-less narrowband [39]	1.9	2.9	8	5.1
Frequency-translational noise-cancelling [40]	2	1.9	4.1	2.2
Transformer-based LNA and trans impedance amplifier with 2nd order filter [41]	2	3.1	7.9	4.8
This work	2.3	1.1	1.2	0.1

4. CONCLUSIONS

The SDARS LNA's size and component count can be beneficially reduced by integrating RF amplifiers, active biasing, impedance matching and filtering into a multi-chip-on-board module. Additionally, the dual-band design also saves on a separate GNSS LNA. The degradation to the noise figure can be prevented by relocating the lossy band-select filter from its traditional pre-LNA position to a mid-LNA position. However, the absence of pre-filtering exposes the 1st stage to out-of-band blockers, but the ill-effects can be mitigated by redistributing the gain to later stages. Amazingly, this minor tweak results in better blocking tolerance than more complicated techniques. Although an SDARS LNA has been demonstrated, the concepts discussed above can be adapted to other LNAs requiring simultaneous low noise and blocking immunity.

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