A Low Power, 3.5-20GHz Tunable LNA with Out-Of-Band Blocker Filtering Based on Compact, Tunable Transmission Line (CTTL) Resonators in 65nm CMOS.

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***Abstract*—We present a tunable LNA for software defined radio based on a compact, tunable transmission line (CTTL) element. The CTTL acts as a passive, widely tunable LC resonance in a cascoded, common source LNA to implement an instantaneously narrowband, multi-octave tunable LNA. The resulting circuit, fabricated in 65nm CMOS, is tunable from 3.5-20GHz, and consumes 12 mW with gain $>$12dB, ≥ -9.6dBV in-band OP1dB, and OOB B1dB up to 31dB higher than the in-band B1dB due to the CTTL-tuned LC filtering. The CTTL-tuned LNA represents a more blocker-tolerant approach to achieving high frequency, software-defined LNAs without significant compromises in other LNA performance metrics.**

***Index Terms*—LNA, software defined radio, wideband, tunable filter, millimeter wave, IoT, transmission line**

I. Introduction

As flexibility and cost efficiency have increased in importance, interest in software-defined radio (SDR) has grown. However, current SDR systems have extensive hardware limitations due to lack of a tunable resonant structure. While many suitably wideband LNAs for SDR have been presented from low-RF to 5G/mmW frequencies ([1-4]), any interference withing their ultra-wide bandwidth will result in compression of the receiver due to the lack of frequency-selective filtering components. In congested or adversarial wireless environments, this greatly limits the practicality of low-power SDR receivers, as high in-band linearity wideband LNAs typically require high power consumption.

An alternative approach to implementing widely-tunable SDR receivers is the passive mixer-first receiver ([5]). Passive downconversion mixers can present a low enough noise figure (NF) to be used as the first component of a front-end, and they provide instantaneously narrowband, widely-tunable RF filtering at their input. This filtering reduces the amplitude of interference within the receiver's tuning range significantly, allowing for blocker-tolerant SDR systems. The caveat to these benefits is high power consumption and NF as such receivers are scaled to frequencies above 6GHz ([5]). Therefore, neither passive mixer-first, nor conventional SDR receivers can operate in the presence of significant blockers at X-band or higher frequencies unless high power consumption is allowed.

In this paper, we present a proof of concept software defined RF LNA which achieves moderate NF up to 20GHz and blocker filtering without compromising in power consumption. This combination of features is achieved via a novel, ultra-widely tunable LC-resonator termed the compact, tunable transmission line (CTTL) ([6]). Because the CTTL provides a practical Q, widely tunable LC resonant circuit, high frequency, software-defined front-end components can be realized with built-in passive filtering. This presents a previously unachievable combination of ultra-wide operating frequency range, low power consumption, and high linearity blocker filtering.

The paper is organized as follows: Section II describes the widely tunable CTTL structure. Section III describes the application of CTTLs to a common-source LNA topology to allow instantaneously narrowband, ultra-wide tuning. Section IV describes the measured performance of the LNA and compares it to the state of the art in wideband and widely-tunable LNAs operable above 6GHz.

II. The Compact, Tunable Transmission Line (CTTL)

The compact, tunable transmission line is a passive, lumped/distributed ultra-widely tunable LC resonant circuit ([6]). It is constructed as a shorted artificial transmission line stub, where a distributed series inductance is uniformly tapped with shunt FET switches sized to present a specific lumped capacitance at each tap point (Fig. 1). As with any shorted transmission line stub, a wide range of reactive components can be approximated over a narrow bandwidth depending on the stub's construction. Unlike a conventional transmission line stub, the capacitive FET switches used in Fig. 1 can be progressively turned on to tune the electrical length of

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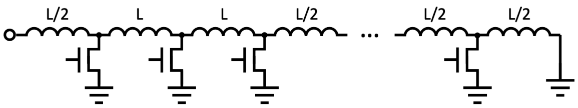

Fig. 1. The basic conceptual CTTL schematic. A shorted stub artificial transmission line is implemented using the parasitic drain capacitance of NFET switches.

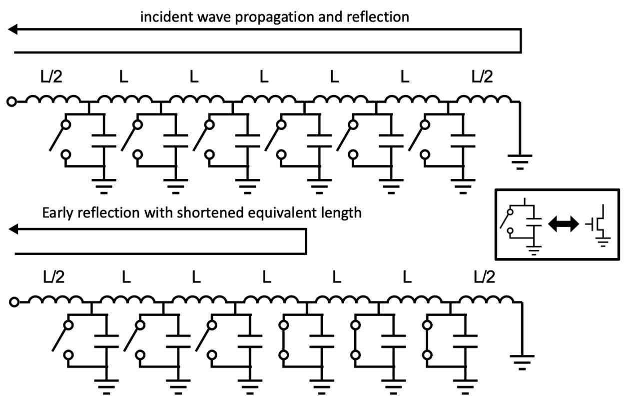

Fig. 2. An illustration of CTTL tuning. Shorting taps to ground with the NFET switches can shorten the effective electrical length of the line.

the stub over an ultra-wide range without affecting the line's characteristic impedance (Fig. 2).

To minimize the required area for the CTTL, the series inductance is implemented as a multi-tap spiral inductor, with FET switches integrated vertically below the spiral (Fig. 3). Therefore only the area required for the total inductance needed is consumed, maintaining a relatively compact footprint. Compared with using individual inductors between each tap, this single-spiral layout results in undesired mutual inductive coupling between transmission line segments. [6] showed that these effects are minimal when the CTTL is used as a $\lambda/2$ or shorter stub as it is here.

III. Low Power, CTTL-Tuned LNA Design

To realize the proposed widely-tunable LNA we can replace the fixed inductors present in conventional LNA designs with CTTL equivalents that are tunable. However the traditional inductively degenerated CS LNA (Fig. 4) requires a series gate inductance that we cannot implement with a CTTL, which is only a suitable replacement for shunt reactive elements.

To solve this, we modify the traditional circuit to use a shunt gate inductance as shown in Fig. 4. The parallel LC circuit formed between L_g and the gate capacitance of the CS FET presents a high, real input impedance at resonance. This real impedance can be tuned with a source inductor, however typically only very high (order-1kΩ) input impedances can be realized in this configuration. In order to lower this input impedance to achieve a power match to a given source impedance (R_s), a variable resistive feedback circuit (R_F) is added (Fig. 4). R_F will add some thermal noise, however the Miller effect causes $R_F >> R_s$ in the matched state if the LNA has significant voltage gain, and so the noise contribution

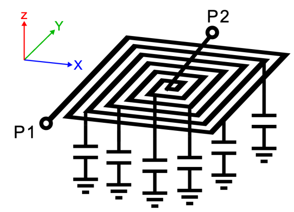

Fig. 3. The 3D layout of the CTTL, where the capacitive NFET switches are integrated below a single multi-tap spiral inductance to save area.

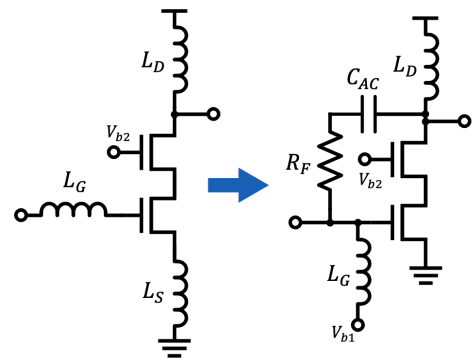

Fig. 4. Left: A conventional fixed-frequency inductively degenerated LNA. Right: A modified topology using only shunt inductors suitable for replacement with CTTLs to achieve wide tuning and input power matching. C_{AC} provides DC blocking only.

of R_F will be small compared with the existing noise floor due to R_s.

While the design on the right in Fig. 4 can be used as is by replacing the fixed inductors with CTTLs, the dimensions and biasing of the CS NFET can only be optimized for simultaneous noise and power matching at a single frequency. From [7], the optimal source impedance for minimum NF ($R_{s,opt}$) is proportional to ω^{-1}. Therefore, non-optimal NF can be expected at all but a single frequency from the design in Fig. 4. To mitigate this issue, we add a tunable CTTL-based matching network to the input of the LNA (Fig. 5). This way, the source impedance can (ideally) be transformed to $R_{s,opt}$ across frequency. One caveat is that the added loss from additional tunable CTTL elements will have a negative impact on the LNAs NF, so a balance must be reached between imperfect noise matching across frequency and tunable matching network loss.

To minimize the number and tuning range of reactive components in the tunable matching network, we observe that a step-up L-matching network can be constructed with a shunt inductor that can be absorbed into the existing shunt CTTL inductance to save one matching network component. To avoid the added loss incurred if C_m is made tunable, we consider if this matching network is sufficiently tunable with a fixed C_m and arbitrary L_m. Because C_m will act simply as a DC blocking capacitor at high frequencies if its value is fixed, we design the CS NFET such that $R_{s,opt} = 50\Omega$ at the highest frequency of operation. Then, if the reactance of

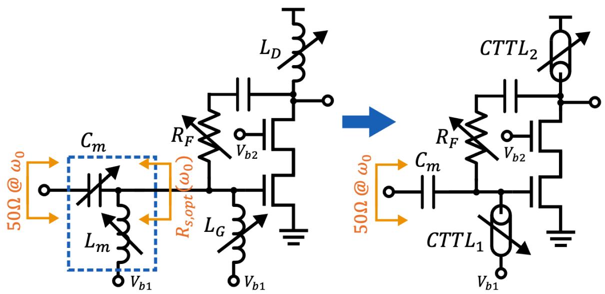

Fig. 5. Left: A tunable, step-up L matching network is added to the LNA to ensure noise matching across frequency despite the varying $R_{s,opt}$ across ω. Right: The final LNA schematic, with two CTTLs to implement the necessary input and output shunt inductance. A fixed C_m is used to improve the matching network Q which results in a lower NF despite an imperfect noise match across frequency.

C_m is canceled with L_m, the impedance transform ratio of this matching network is proportional to ω^{-2}. At very low frequencies, this will cause a significant noise mismatch (as $R_{s,opt} \propto \omega^{-1}$), however at lower frequencies the intrinsic CS device noise drops. Therefore, for a desired LNA NF, we can better tolerate a noise mismatch at lower frequencies. A fixed C_m matching network is preferred to no matching network because power matching with R_F introduces some noise and causes output loading, particularly at lower frequencies where a smaller R_F is required. Therefore the final LNA design concept is given in Fig. 5 on the right.

The manufactured design has two additional details of note. One is the addition of small binary-weighted capacitor banks in parallel with each CTTL. This allows for fine-tuning between CTTL tap settings, which are suitable for wide, coarse tuning. The second is the use of I/O devices for the CTTL's digital bit drivers, as the AC ground for each CTTL is the input bias level and V_{DD}, respectively. With this in mind, the digital drivers for each CTTL are designed to swing from ground to the maximum allowed V_{GS}, such that CTTL FETs can be fully turned on despite their positive source voltage. This ensures optimal on-resistance and linearity for the CTTL FETs.

IV. Measured Performance

The LNA was fabricated in a TSMC 65nm CMOS technology and occupies 710 x 376μm excluding pads (Fig. 6). The LNA achieves a tuning range of 3.5GHz to 20GHz and consumes 12mW on a 1.4V supply. At this power setting, the minimum NF ranges from 3.5dB to 7.9dB ($\leq$6dB below 16GHz), and the output -1dB compression voltage (OP1dBV) varies from -9.6 to -3.7dBV (Fig. 7). Due to the active NFET parasitic capacitance which must be resonated by the CTTLs and the increasing CTTL switch losses at higher frequency settings, there is significant gain variation as the LNA is tuned. With a higher supply and/or input bias, the LNA is capable of higher gain and lower NF at the cost of added power consumption. Conversely, the LNA can be operated at a lower bias to reduce gain at the lower end, and can be run on a lower supply to further save power at the cost of increased NF.

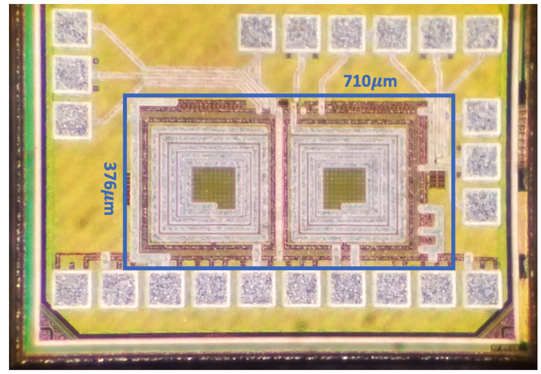

Fig. 6. The manufactured LNA.

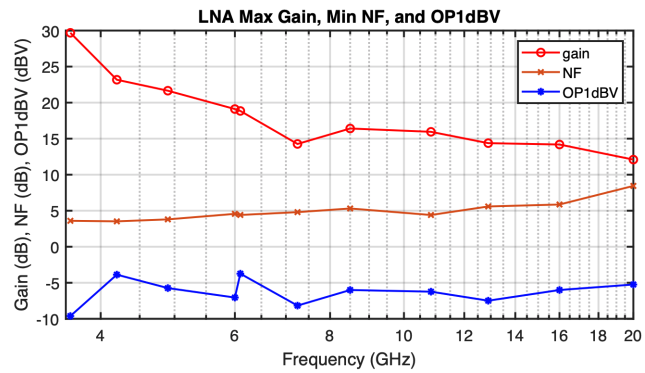

Fig. 7. The measured peak gain, minimum NF, and OP1dBV at 12mW power consumption across frequency.

Figure 8 shows the instantaneously narrowband, widely tunable performance of the LNA for a few representative settings, all also measured at 12mW power consumption. Figure 9 shows the measured input-referred B1dB and IIP_3 versus offset frequency for various center frequencies. In-band, the B1dB and IIP_3 vary across center frequency due to the gain variation (Figs. 7,8), however at large offsets OOB B1dB and IIP_3 improve due to the built-in tunable filtering provided by the input matching network, improving OOB blocker tolerance.

A comparison of this LNA and similar published LNAs and RX front-ends is given in Table I. [1-4] represent conventional wideband LNAs, while [5] is a passive-mixer-first receiver. We find that, compared to wideband LNAs, this work has comparable power consumption, somewhat higher NF, and higher IB and OOB OB1dBV and OIP_3. Due to the large difference in gain between [1-4] and the presented work, we compare output-referred linearity measurements such that gain differences between this work and [1-4] is normalized. The problem of poor interferer tolerance in [1-4] is particularly highlighted in [2], where the cost of operating over such a wide range is that any significant interference in the entire 1.6 - 28GHz band will de-sensitize the LNA. Compare that to this work, where when operating at 8.5GHz a blocker at 3.5GHz did not cause 1dB compression of the desired signal until the input ESD protection clamped the input at +4dBm.

TABLE I
COMPARISON TO THE STATE OF THE ART WIDEBAND LNAS

	[1]	[2]	[3]	[4]	[5]	This Work
Technology	65nm CMOS	90nm CMOS	65nm CMOS	22nm FDSOI CMOS	65nm CMOS	65nm CMOS
Frequency Range (GHz)	7.6 - 29	1.6 - 28	11.8 - 37.2	24 - 43	9 - 31	3.5 - 20
Gain (dB)	$\leq$10.7	9.6 $\pm$ 1.1	$\leq$12.5	18.2 - 23	>40	12 - 29
NF (dB)	4.5 - 5.6	3.66 $\pm$ 0.74	2.95 - 4	3.4 - 4.3	12.5 - 17.5	3.5 - 7.9
OP1dBV (dBV)	$\leq$-12.2*	-12.4*	<-12.3*	$\leq$-15*	>-18#	-9.6 - -3.7
OOB+ OB1dBV (dBV)	$\leq$-12.2*	-12.4*	<-12.3*	$\leq$-15*	+21 - +31	-9 - +14
IB/OOB+ OIP_3 (dBV)	-0.91* / -0.91*	+0.59* / +0.59*	-1.5* / -1.5*	<-3* / <-3*	-10# / +48*	+1 - +5/+4 - +24
Power Consumption (mW)	12.1	21.6	5.4	12.1	73 - 162	12
Area (mm^2)	0.3	0.139	0.25	0.47	n/r	0.27

+Reported only for frequency offsets within the total operating frequency range, e.g. in-band OB1dBV for non-tunable, wideband LNAs).
*Estimated from IIP_3, IP1dB, and gain as needed. #Estimated from in-band B1dB plot and gain.

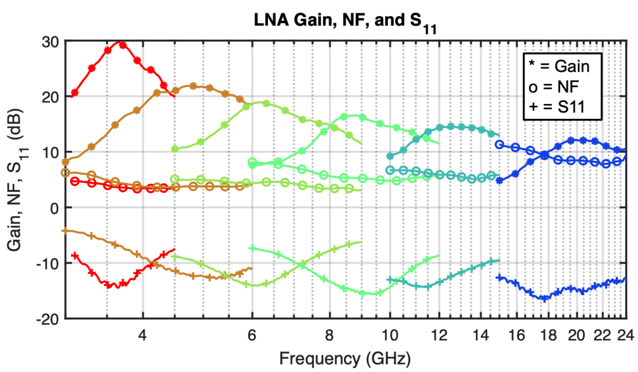

Fig. 8. Gain, NF, and S_{11} curves for the LNA tuned to various center frequencies from 3.65GHz to 20GHz. Effectively continuous tuning is achieved between these representative plots.

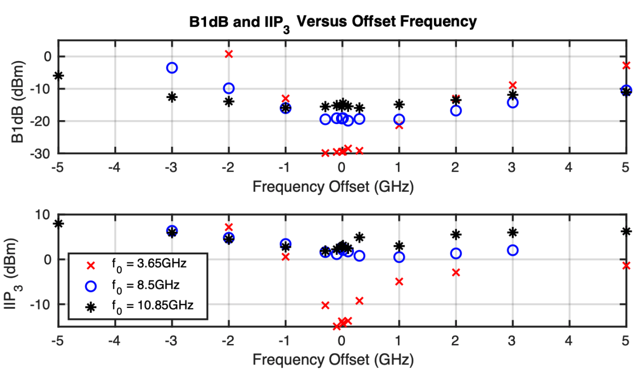

Fig. 9. Measured input-referred B1dB and IIP_3 versus frequency offset for three center frequencies. OOB B1dB and IIP_3 show up to >20dB improvement due to input CTTL filtering. For the IIP_3 measurements, offset frequency is defined as $f_0 - \frac{f_1+f_2}{2}$, where f_1 and f_2 are the two input tones.

While this work represents a significant improvement in wideband LNA blocker tolerance, [5] does present higher OOB linearity and much narrower instantaneous bandwidth, which can better reject blockers at small offsets. However, unlike this work, [5] requires major compromises in NF and power consumption compared with [1-4]. Therefore the CTTL-tuned LNA is able to provide moderate blocker filtering with little NF degradation, as CTTL tuning enables practical multi-octave tunable LC filters with zero DC power consumption. In a higher performance process such as those used in [4] and [6], the CTTL-tuned LNA can achieve tighter filtering, lower noise, and higher frequency operation due to the lower FET switch losses. At high (>8GHz) frequencies, there is no technique to the authors' knowledge that can provide this combination of improved interference tolerance without major compromise on tuning range, power consumption, and/or NF.

V. CONCLUSION

In this paper, we present a fully passive, compact, ultra-widely tunable transmission line stub (the CTTL) and use it to realize a 3.5GHz to 20GHz tunable LNA including a tunable input matching network. This passive, widely-tunable LC filtering allows for high OOB linearity without additional power consumption, resulting in a software-defined LNA with state of the art blocker tolerance and without large compromises other LNA performance metrics.

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