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ENHANCED FREQUENCY BAND WIDEBAND RECEIVER USING MILLER *N*-PATH BANDPASS FILTER

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Abstract. This paper presents the design and modelling result of the wideband receiver topology with an enhanced frequency band using Miller *N*-path bandpass filter and harmonic-rejection mixing technique. The wideband receiver has the form of monolithic microwave integrated circuits (MMIC) based on domestic GaAs pHEMT technology. The receiver consists of low noise amplifier (LNA), commutated network and harmonic recombination circuit. When using inductors to compensate the parasitic capacitances, the bandwidth of the LNA significantly increases from 0–2.3 GHz to 0–5 GHz, thereby increasing the receiver frequency band to 0.3–3 GHz. The receiver achieves a gain of 15 dB, a noise figure of < 4 dB, an out-of-band IIP3 of +8 dBm, and a harmonic-rejection ratio at the third- and fifth-order local oscillator harmonics of > 50 dB.

Keywords: wideband receiver, multi-band receiver, wideband LNA, harmonic-rejection mixer, Miller *N*-path bandpass filter, MMIC, GaAs pHEMT

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ШИРОКОПОЛОСНЫЙ ПРИЕМНИК С РАСШИРЕННЫМ ДИАПАЗОНОМ ЧАСТОТ ПРИ ИСПОЛЬЗОВАНИИ ПОЛОСОВОГО *N*-КАНАЛЬНОГО ФИЛЬТРА МИЛЛЕРА

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Аннотация. Представлены разработка и результаты моделирования топологии широкополосного приемника с расширенным диапазоном частот при использовании полосового *N*-канального фильтра Миллера и метода подавления гармоник. Широкополосный приемник выполнен в виде СВЧ монолитных интегральных схем на основе отечественной GaAs pHEMT технологии. Приемник состоит из малошумящего усилителя (МШУ), коммутируемой цепи и цепи рекомбинации гармоник. При использовании катушки индуктивности для компенсации паразитных емкостей, полоса частот МШУ значительно увеличивается с 0–2,3 ГГц до 0–5 ГГц, тем самым увеличивая полосу частот приемника до 0,3–3 ГГц. Приемник достигает коэффициента усиления 15 дБ, коэффициента шума < 4 дБ, внеполосной IIP3 +8 дБм, коэффициента подавления гармоник на гармониках частоты гетеродина третьего и пятого порядка > 50 дБ.

Ключевые слова: широкополосный приемник, многодиапазонный приемник, широкополосный МШУ, смеситель подавления гармоник, полосовой *N*-канальный фильтр Миллера, МИС, GaAs pHEMT

Финансирование: Производство интегральной микросхемы выполнено за счет средств Минобрнауки России по государственному заданию на выполнение НИР «Разработка методики прототипирования электронной компонентной базы на отечественных микроэлектронных производствах на основе сервиса MPW» (FSMR-2023-0008) в рамках федерального проекта «Подготовка кадров и научного фундамента для электронной промышленности».

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Introduction

With the increase in the number of standards in the frequency band from 0.3 GHz to 6 GHz (such as LTE, 5G, ...), the number of narrowband receivers in devices designed for each of their own standards increases. Then the device becomes bulky and expensive. Therefore, it is necessary to develop a wideband (multi-band) receiver capable of receiving several standards. In a wideband receiver, such blocks as low noise amplifier (LNA) and mixer are used for several bands and the off-chip surface acoustic wave (SAW)-based bandpass filters are removed. Thus, the size and cost of the device will be saved.

Due to the lack of the off-chip SAW filters, out-of-band blockers enter the receiver without filtering and desensitize it. Therefore, firstly, the blocks located near the antenna, such as the LNA and mixers, must have extremely high linearity. Secondly, these high-power blockers must be filtered as early as possible in the receiving path in order to reduce the linearity requirements for subsequent blocks. In other words, this means that in the receiving path these out-of-band blockers must be filtered before they are amplified. In wideband receivers *N*-path filter is a popular choice for on-chip blocker filtering because of their wide tuning range and high Q factor [1–5].

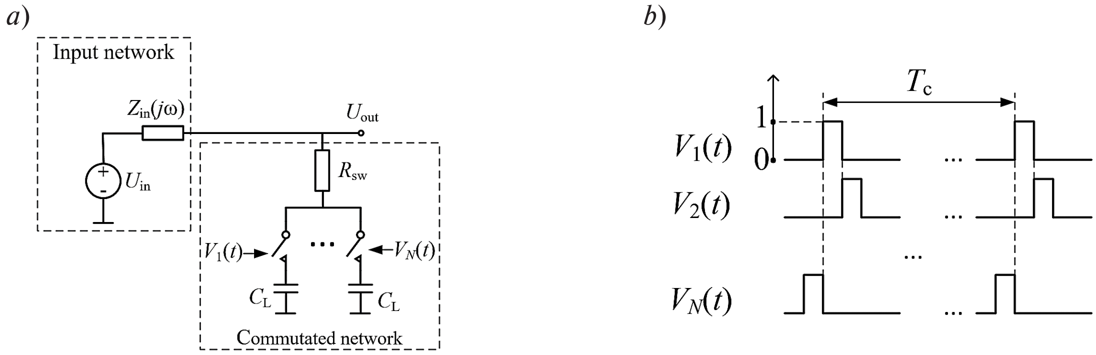

Fig. 1. Schematic of N-path filter (a), normalized control function of the k-th switch (b)

This paper describes the design of wideband receiver with enhanced frequency band using N-path filtering and harmonic-rejection mixing techniques with Miller effect based on the domestic GaAs pHEMT technology.

Features of N-path filtering technique

Fig. 1a, presents the circuit of a N-path filter. The input network is modeled by a voltage source $U_{in}(\omega)$ with its impedance $Z_{in}(j\omega)$. In the commutated network N switches are periodically commutated with the switching frequency f_c using the non-overlapping square pulses signal $V_{0k}(t)$ (Fig. 1b, where $V_k(t) = V_{0k}(t)/V_0$ is normalized control function of the k-th switch; V_0 is the maximum value of the pulses). R_{sw} is the resistor of the switch when it is ON.

Using the method used in [6], when $\omega_c/2 < \omega < 3\omega_c/2$ (where $\omega_c = 2\pi f_c$) the output voltage $U_{out}(\omega)$ of the N-path filter is calculated by:

$$U_{out}(\omega) = \left[R_{sw} + \frac{c(\omega) Z_{in}(j\omega)}{\left(1 + g(\omega)\right)\left(R_{sw} + Z_{in}(j\omega)\right)} \right] \frac{U_{in}(\omega)}{R_{sw} + Z_{in}(j\omega)}, \tag{1}$$

where:

$$c(\omega) = \frac{N \sin\left(\left(\pi - \frac{\pi}{N}\right) b(\omega)\right) \sin\left(\frac{\pi b(\omega)}{N}\right) Z_{CL}(j\omega_c)}{2\pi \sin\left(\left(\frac{\omega - \omega_c}{\omega_c}\right)\pi\right)}; \tag{2}$$

$$Z_{CL}(j\omega_c) = \frac{1}{j\omega_c C_L}; \quad b(\omega) = \frac{\omega}{\omega_c};$$

$$g(\omega) = \sum_{l=-\infty}^{+\infty} \frac{c(\omega)}{\left(b(\omega) + lN\right)^2 \left(R_{sw} + Z_{in}(j\omega + lNj\omega_c)\right)}.$$

For an ideal N-path filter, $Z_{in}(j\omega)$ is the resistor R_S. Then from (1) we have the transfer function of the N-path filter in the range $\omega_c/2 < \omega < 3\omega_c/2$:

$$K(\omega)=\frac{U_{\text{out}}(\omega)}{U_{\text{in}}(\omega)}=\frac{R_{\text{sw}}}{R_{\text{sw}}+R_{\text{S}}}+\frac{\dfrac{c(\omega)R_{\text{S}}}{R_{\text{sw}}+R_{\text{S}}}}{R_{\text{sw}}+R_{\text{S}}+\sum\limits_{l=-\infty}^{+\infty}\dfrac{c(\omega)}{\left(b(\omega)+lN\right)^2}}\approx$$

$$\approx\frac{R_{\text{sw}}}{R_{\text{sw}}+R_{\text{S}}}+\frac{c(\omega)}{R_{\text{S}}+\sum\limits_{l=-\infty}^{+\infty}\dfrac{c(\omega)}{\left(b(\omega)+lN\right)^2}}. \tag{3}$$

When ω is close to ω_c, then $(\omega-\omega_c)/\omega_c\approx 0$ and $b(\omega)=\omega/\omega_c\approx 1$. Then from (2) we see that $|c(\omega)|$ has a much larger value than R_S. Then formula (3) becomes:

$$K(\omega)=\frac{R_{\text{sw}}}{R_{\text{sw}}+R_{\text{S}}}+\frac{c(\omega)}{R_{\text{S}}+\sum\limits_{l=-\infty}^{+\infty}\dfrac{c(\omega)}{\left(b(\omega)+lN\right)^2}}\approx\frac{1}{\sum\limits_{l=-\infty}^{+\infty}\dfrac{1}{\left(1+lN\right)^2}}.$$

For wideband receivers, N is usually 8. Then $K(\omega)\approx 1$. That means that when the frequency ω (ω is close to ω_c) is within the passband of the N-path filter, the maximum value of transfer function $K_{\max}\approx 1$.

On the other hand, when the frequency ω is far from ω_c, $|c(\omega)|$ is very small compared to R_S because $|Z_{CL}(j\omega_c)|$ is very small compared to R_S. Then formula (3) becomes:

$$K(\omega)\approx\frac{R_{\text{sw}}}{R_{\text{sw}}+R_{\text{S}}}\ll 1. \tag{4}$$

This means that when the frequency ω is outside the passband of the N-path filter, the transfer function of the N-path filter $K(\omega)$ is very small compared to 1.

Miller *N*-path bandpass filter

Formula (4) shows that the out-of-band interferences rejection capability of the N-path filter is limited by $R_{sw}/(R_{sw}+R_S)$. Thus, to decrease $K(\omega)$, when ω is outside the passband of the N-path filter, it is necessary to decrease R_{sw} or/and increase R_S. If R_{sw} is too small, the parasitic capacitance of the switches will be very large and increase the leakage of the control signal $V_{0k}(t)$. Therefore, a more feasible way is to increase R_S. In addition, [7] also shows that the bandwidth of the N-path filter is determined by: $BW=1/(\pi N R_S C_L)$. For standards with small bandwidths (e.g. from a few hundred kHz to a few MHz), C_L has a fairly large value and significantly increases their area on the chip. Therefore, increasing R_S is also necessary.

Article [7] shows how to increase R_S by placing the commutated network at the LNA's feedback. Then by using Thevenin equivalent model the internal resistance of the equivalent source will increase $(1-A_0)$ times, where A_0 is the voltage gain of LNA and needs to be a negative real number. For the receiver to work in a wide frequency band, A_0 needs to keep its value constant in that frequency band. With the LNA design in [7], $|A_0|$ is often reduced at 2–3 GHz due to parasitic capacitances, thereby reducing the frequency band of the receiver.

Design of LNA

To increase bandwidth of the LNA in this paper, we add inductors in series with the load resistors of each stage of the LNA developed in [7]. These inductors will compensate the parasitic capacitances and keep $|A_0|$ from decreasing at high frequencies, thereby increasing the bandwidth of the LNA (Fig. 2*a*).

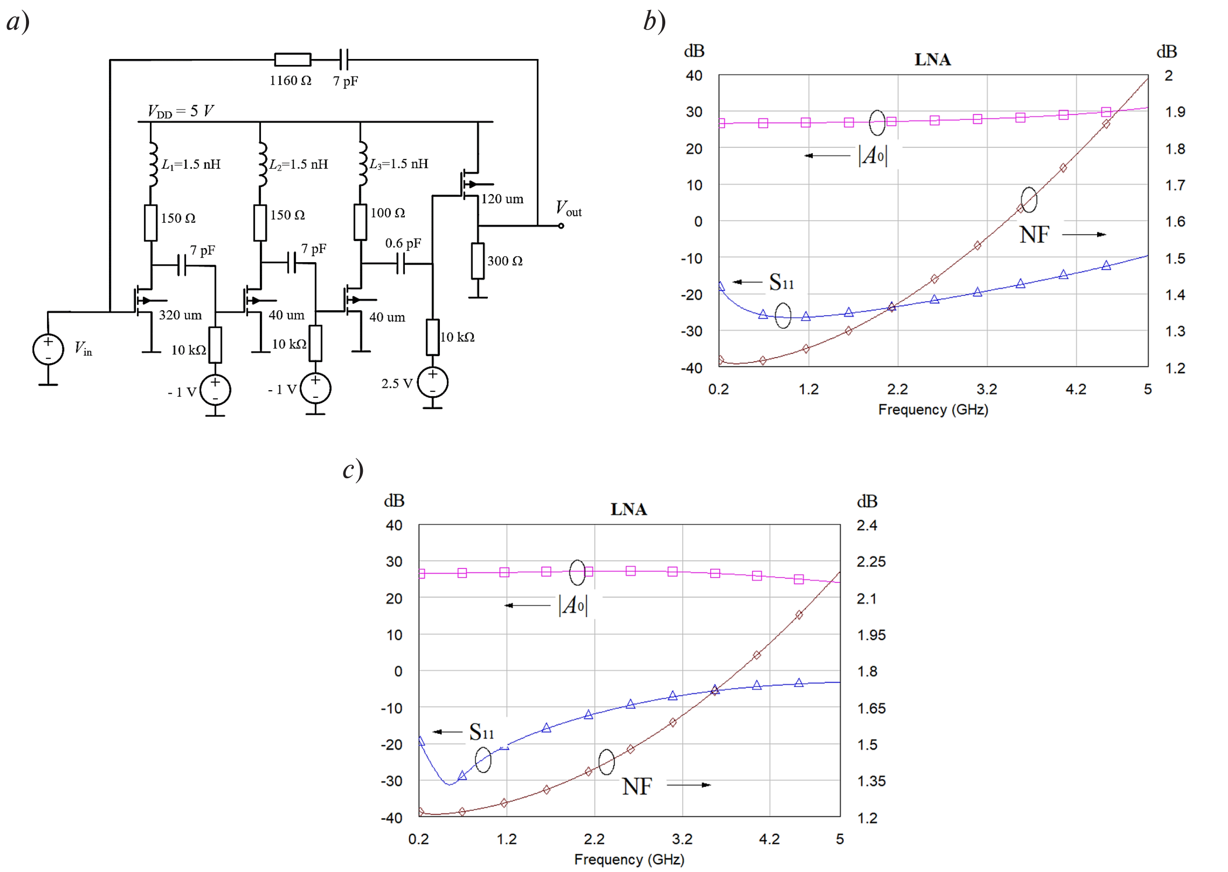

Fig. 2. Schematic of LNA (a), frequency responses: S_{11}, noise figure NF and voltage gain $|A_0|$ with inductors (L_1, L_2, L_3) (b) and without inductors (L_1, L_2, L_3) (c)

The LNA is designed based on the domestic GaAs pHEMT technology using Microwave Office circuit design tool. Frequency responses (S_{11} and $|A_0|$) of the LNA design with inductors (L_1, L_2, L_3) and without inductors (L_1, L_2, L_3) are shown in Fig. 2b and 2c, respectively. The LNA design with inductors ensures flat voltage gain $|A_0| \approx 27$ dB, noise figure NF < 2 dB and $S_{11} < -10$ dB in the frequency range from 0.2 GHz to about 5 GHz. Meanwhile, for the LNA design without inductors, $S_{11} > -10$ dB when the frequency is greater than 2.5 GHz (Fig. 2c). In addition, the voltage gain $|A_0|$ is also reduced at frequencies around 4–5 GHz.

Design of wideband receiver

The schematic of wideband receiver is presented in Fig. 3a. It consists of LNA, commutated network and harmonic recombination (HR) circuit. The LNA and commutated network form Miller N-path bandpass filter, which acts to pass the desired signal and filter the interferences at the output of the LNA. Therefore, these interferences cannot cause nonlinear effects to the LNA. In addition, in this design, $R_S C_L >> T_c$ (where T_c – period of $V_k(t)$), so the Miller N-path bandpass filter also acts as a mixer [8–9]. This mixer converts the RF frequency voltage at the output of the LNA to the baseband voltage at the capacitors C_L. In this case, the local oscillator (LO) frequency f_{LO} of the mixer is equal to the switching frequency f_c.

On the other hand, due to the lack of filtering of the bandpass filter at the input of the receiver, the mixer converts not only the desired signal at the frequency $f_{in} \approx f_{LO}$, but also the interferences at some harmonics of the LO frequency kf_{LO}, ($k \neq \pm 1$). To solve this problem, a HR circuit is used. The principle of operation of the HR circuit is that a "pseudo-sine-LO" signal is generated. Unlike the $V_k(t)$

a) *b*)

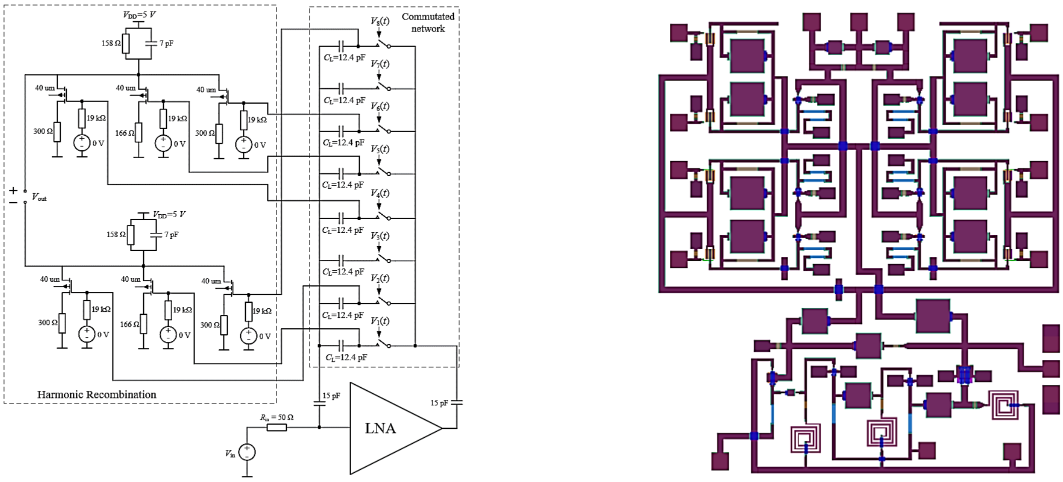

Fig. 3. The schematic (*a*), topology (*b*) of wideband receiver

signals, which have a square wave shape, the "pseudo-sine-LO" signal has a shape similar to a sine wave. Therefore, it does not contain 3rd and 5th harmonics. Consequently, interferences in these harmonics are eliminated at the output of HR circuit. In Fig. 3*a*, the baseband voltages at the capacitors C_L are converted to currents with corresponding transconductances (with a ratio of $1:\sqrt{2}:1$) by the common-source (CS) amplifiers. They are then summed and converted to voltages at the outputs of these CS amplifiers.

The wideband receiver is designed based on the domestic GaAs pHEMT technology using Microwave Office circuit design tool (Fig. 3*a*). MMIC topology of the receiver designed on its basis (Fig. 3*b*). Its performances are shown in Table.

Table

Performances of the wideband receiver

Parameters	Value
Frequency band of input signal, GHz	0.3–3
Gain, dB	15
Noise figure, dB	< 4
Out-of-band IIP3, dBm	8
HR3, dB	50
HR5, dB	52

where HR3 and HR5 are the ratios of the conversion gain for the desired signal to that for the signals at 3rd and 5th harmonics respectively.

The frequency band of the receiver is reduced compared to the frequency band of LNA due to the parasitic elements of the switches. Simulation results show that if the LNA does not use the inductors (L_1, L_2, L_3), the frequency band of receiver is only 0.3–1.5 GHz.

Conclusion

The design of wideband receiver with enhanced frequency band using Miller N-path bandpass filter is described. By using inductors to compensate the parasitic capacitances, the bandwidth of the LNA is significantly increased from 0–2.3 GHz to 0–5 GHz, thereby increasing the receiver frequency to 0.3–3 GHz. The MMIC topology of the receiver is designed and simulated based on the domestic GaAs pHEMT technology using Microwave Office circuit design tool. The performances of the receiver in its frequency band: gain is 15 dB, noise figure is < 4 dB, out-of-band IIP3 is 8 dBm, HR3 and HR5 are 50 and 52 dB, respectively.

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