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ПРИКЛАДНЫЕ АСПЕКТЫ РАДИОАСТРОНОМИИ, РАДИОФИЗИКИ И ЭЛЕКТРОНИКИ

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HIGH SENSITIVITY 0.5 TO 19.5 GHZ RECEIVER WITH 1.1-GHZ INSTANTANEOUS BANDWIDTH

A wideband high sensitivity microwave receiver operating within 0.5 to 19.5 GHz and providing a 1.1-GHz instantaneous bandwidth is described. The receiver shows a noise figure as low as 10 dB and the input third-order intercept point up to 10 dBm as well. Also, the receiver is characterized by a low spurious response and extremely low residual phase noise, too. Essential design principles of the receiver are given and discussed.

Keywords: receiver, wideband, low-noise, microwave

1. Introduction

Wideband microwave receivers are usually considered to be an essential part of electronic intelligence (ELINT), electronic countermeasures (ECM), and electronic counter-countermeasures (ECCM) systems [1, 2]. But an explosively growing usage of wireless technologies [3, 4], observed in recent years, arouses a great interest for such receivers in a number of other applications including monitoring of complex electromagnetic environment for virtually everyday usage [5].

Another important factor is a quantum leap in a number of spread spectrum applications including high resolution radars, high capacity wireless communication systems, and a variety of systems designed to achieve a low intercept probability [6–8]. The above applications obviously require a broader instantaneous receiver bandwidth and a higher sensitivity as against those accessible in most recent years. On the other hand, an increasing commercial availability of the state-of-the-art monolithic microwave integrated circuits (MMIC), passives, and integrated microwave assemblies noticeably facilitates the development of modern receivers and opens new opportunities for alternative design approaches.

A modern versatile receiver is not only a simple signal conditioner for detecting and recognizing inherent for ELINT, ECM, and ECCM systems, but often a part of highly automated measurement setup intended for more or less accurate estimation of signal strength and working usually together with some digital data acquisition and signal processing system. It implies introduction of self-calibration capabilities as well as minimizing the residual spurs response of the receiver. Indeed, wideband receivers generally utilize several frequency conversions and, thus, include a number of local oscillators and mixers producing a variety of spurious signals. On the other hand, the advanced signal processing procedures for automated signal detection and recognition are based on the spectral analysis and hence include inherently the comparison of the strength of a received signal with some threshold in a frequency domain. This threshold eventually determines the real sensitivity of the complete system. In case of no spurs, the peak sensitivity depends on the receiver noise figure only. Due to spurs, either the threshold should be selected higher to keep false alarm rate constant, that evidently leads to some degradation in system sensitivity, or to use rather sophisticated and restrictedly applied algorithms for spurs elimination.

Just to meet the above challenges, a wideband receiver covering the 0.5 to 19.5 GHz frequency range, providing 1.1 GHz output bandwidth, and demonstrating a noise figure of less than 10 dB, and –80 dBm level of internally generated spurs at the maximal gain has been recently developed. Below, the essential design principles of such a receiver are described and discussed.

2. Receiver Design Principles

2.1. System Overview

A simplified block-diagram of the receiver is shown in Fig. 1. The receiver possesses a standard configuration of inputs and outputs. Namely, there is the only radio frequency (RF) input accepting signals from the frequency range of 0.5 to 19.5 GHz, a wideband (WB) intermediate frequency (IF) output, a narrowband (NB) IF output, and two video outputs which are simply outputs of envelope detectors coupled to the corresponding IF outputs. The bandwidth of wideband IF output signals is 1100 MHz centered at 1850 MHz, whereas the narrowband IF output is characterized by switchable bandwidths of ±5, ±10, and ±20 MHz centered at 160 MHz. As is seen from Fig. 1, some receiver circuits are common for both the wideband and narrowband channels, and, therefore, the frequency and the gain cannot be chosen absolutely independent for each of them. In part, the NB channel frequency can deviate within ±550 MHz from that of the WB channel only. Double and quadruple frequency conversions for the WB and NB channels are used, correspondingly. Two different first intermediate frequencies and, thus, two downconverters are used in the receiver.

2.2. Design Approaches

As can be seen from Fig. 1, the receiver architecture differs from that to be of common use. Actually, in most cases, a circuit providing signal filtration is implemented directly at the receiver input, just to ensure an adequate performance in a complex electromagnetic circumstance [9]. Usually, a tunable filter with a passband being only just a bit wider than the receiver bandwidth is often used before any gain stages or mixers. This prevents the appearance of spurious signals induced by fairly strong out-of-band signals which are mixed in nonlinear circuits and produce then a variety of frequency diverted components.

However, this conventional approach furthers reduction of receiver noise figure significantly. This is due to the lack of tunable low-loss passband filters with a wide enough bandwidth. Commercially available Yttrium-Iron-Garnet (YIG) filters possess at best a 3-dB bandwidth of 500 MHz, moreover a single filter does not cover the entire range of 0.5 to 19.5 GHz. On the other hand, using a switchable filter bank results in fairly large insertion losses due to the necessity of utilizing multi-stage broadband switches.

Due to the above reasons, in the receiver in question the signal chain begins with a broadband low noise amplifier (LNA). A block-diagram of the receiver input circuit is shown in Fig. 2. The LNA is of Avago produced AMMC-5024 type. There is no frequency selective circuit before the LNA. A comparatively good linearity of modern wideband distributed LNA allows keeping the total dynamic performance of the receiver adequate for the overwhelming majority of applications. In addition, the signal produced by the detector, built-in to LNA die, is coupled to a control circuitry. It makes possible a continuous broadband monitoring of the receiver input signal independently of a tuned frequency, allowing, for example, detection of blocking condition, when a strong signal causes LNA saturation [10].

A coaxial switch allows connecting a noise source to the input of the receiver signal chain that is

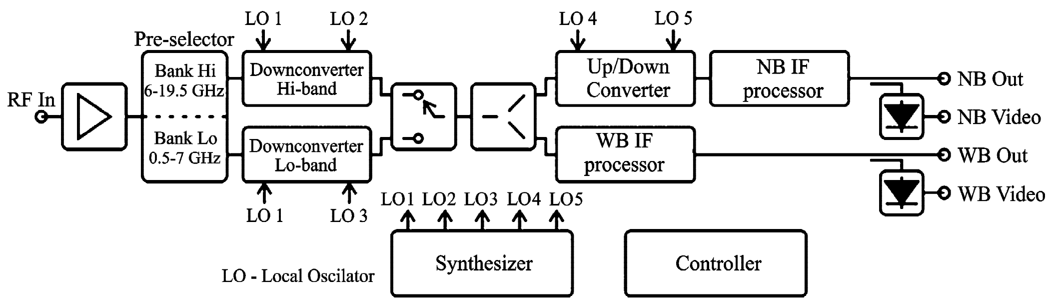

Fig. 1. Block-diagram of receiver

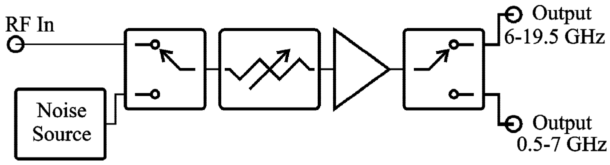

Fig. 2. Block-diagram of receiver input circuit

used for providing the receiver calibration (see Section 3).

A programmable mechanical relay attenuator makes possible to work correctly with even very strong input signals.

A digital attenuator with the range of 15.5 dB and the step of 0.5 dB follows directly the LNA allowing precise gain regulation. A single pole double throw switch (SPDTS) allows preliminary selection of a particular frequency band. The LNA, the attenuator, and the switch are integrated, along with power supply conditioning, control and interface circuits, into a single assembly.

The pre-selector – “pre” means implementation of frequency selectivity before the first mixer – in the receiver is implemented as a switchable filter bank, consisting of 9 channels totally, grouped into two sub-banks, Hi and Lo, for the 0.5 to 7 GHz and the 6 to 19.5 GHz frequency bands, respectively, as is shown in Fig. 3. Each channel includes an amplifier to compensate losses in the filters and switches. The 6 to19.5 GHz band is divided into 4 sub-bands, whereas the 0.5 to 7 GHz band is divided into 5

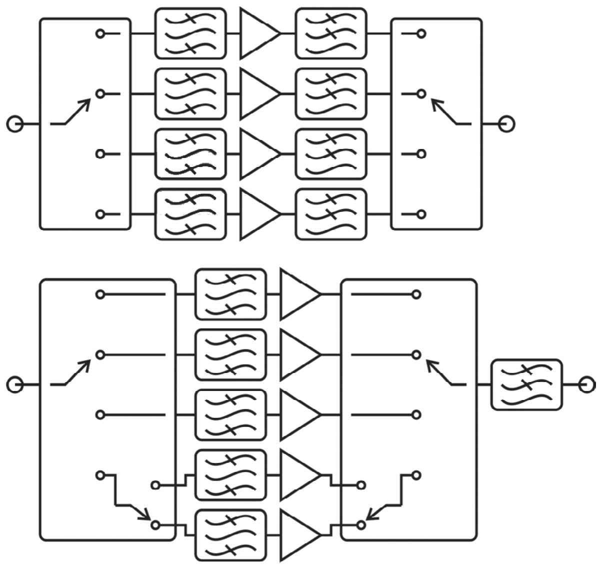

Fig. 3. Block-diagram of switchable filter bank

sub-bands as is indicated in Table 1. In total, the sub-bands cover the entire frequency range of 0.5 to19.5 GHz with overlapping of 1.1 GHz providing seamless tuning of the receiver over the aforesaid range. The supply voltage of each amplifier is switched synchronously with the corresponding sub-band in order to improve isolation between the channels.

Each filter in the Lo sub-bank is simply a sub-octave one, except that possessing the bandwidth of 0.5 to 2.8 GHz. It is enough to ensure a spurious free frequency downconversion over all sub-bands apart from the mentioned one, for which it is naturally impossible. To provide an additional image rejection, there is a low-pass filter, which is common for all sub-bands in the Lo filter sub-bank.

Within the Hi filter sub-bank, sub-bands are distributed almost evenly. Each amplifier is followed by a low pass filter ensuring harmonics filtration and image rejection inasmuch as cavity bandpass filters do not provide a fairly wide stopband. The switches utilize a P-i-N based MMIC of MASW-004100-1193 type produced by M/A-COM Technology Solutions, thus resulting in the total insertion losses of less than 1.5 dB and facilitating considerably the achieved improvement in the receiver noise figure.

Note, that the number of bands in the Hi bank is much lower than that needed to ensure a truly spurious free frequency downconversion. Instead, the state-of-the-art mixers of T3 series produced by Marki Microwave are used in the receiver [11]. Such mixers manifest an extremely low spurious response of less than –70 dB at –10 dBm input power of the receiver allowing approaching the total SFDR as of –60 dB.

Table 1. **Frequency mapping of the receiver bands**

Band	Passband, MHz
Lo bank	
Band 1	0.5–2750
Band 2	1850–3250
Band 3	2350–3850
Band 4	2950–4950
Band 5	4050–7050
Hi bank	
Band 1	6150–9050
Band 2	8150–12050
Band 3	11150–15050
Band 4	14150–19550

Both downconverters utilize practically the same design with the two gain blocks along with filters between them. The downconverter circuitry does not allow gain regulation. Such a trade-off simplifies the receiver design significantly, though slightly hampers approaching maximum possible dynamic range. The first intermediate frequencies are 15750 and 4850 MHz for the input frequency bands of 0.5–7 GHz and 6–19.5 GHz, respectively.

The drive level of each mixer in the downconverters can be varied to some margins. This allows ensuring their optimum performance adaptively. For example, such a possibility is used to provide a gain dependent regulation of the drive level just to minimize the noise figure and improve the spurious response in some particular frequency sub-bands.

In order to prevent the appearance of spurious signals caused by inevitable leakages and taking into account that just a single downconverter is engaged at a time, the signals of the local oscillators are coupled only to the active downconverter.

The intermediate frequency (IF) circuitry follows the downconverters and comprises an up/downconverter to tune the NB channel frequency, signal conditioners for WB and NB IF channels, and video detectors shown in Fig. 1. Both signal conditioners include gain blocks, filters, and digital attenuators to allow gain regulation.

The synthesizer has been designed to approach a very low amount of phase noise added and spurious signals induced on the receiver signals. In order to minimize the phase noise at large frequency offsets, the frequencies of the tunable local oscillators are synthesized with double-loop Phase-Locked Loops (PLL) by using highly stable Dielectric Resonator Oscillator (DRO) based sources. As a result, the phase noise spectral density never exceeds –105 dBc/Hz at 10 kHz offset and –120 dBc/Hz at 1 MHz offset. A Direct Digital Synthesizer (DDS) is used in order to minimize the frequency switching time of LO4 (see Fig. 1) and to provide a small frequency step allowing agile frequency scanning for the NB channel.

All receiver assemblies support digital interfacing by using a Serial Peripheral Interface (SPI) bus. A built-in controller is based on Xilinx Spartan 6 FPGA that allows implementing elaborated algorithms to ensure the receiver agility. The controller monitors a number of both analog and discrete signals produced by the sensors allowing extended built-in test capabilities as well as a failsafe receiver operation.

3. Receiver Calibration

The receiver signal chain includes a number of stages with practically a one-way dependency of the gain (or insertion losses) on temperature. Hence, the contribution from majority of them is added coherently, thus resulting in a fairly large variation of the total receiver gain with temperature. In order to ensure an accurate receiver performance over a temperature range, some additional devices have been introduced in the receiver. They include a noise source and the calibration switch (see Fig. 2). By using these devices, the conventional Y-factor method [12] based on successive measurements of the output signal strength with and without a noise source connected to the receiver input has been realized. This procedure enables to easily estimate the receiver noise figure and gain.

The accuracy of calibration is determined essentially by that of power measurement. In the receiver, the calibration accuracy of ±1.5 dB over the entire frequency and temperature ranges has been achieved by using the usual video detectors (see Fig. 1) as power meters. This allows simplifying the receiver design complexity.

The maximal gain variation to be fixed is +7 to –3 dB. This allows accurate receiver operation within the temperature range of 0 to 50 °C keeping both the noise and dynamic performance at a specified level. The receiver produces a special signal to external devices, if the present temperature measured inside them differs from that measured at the last successful calibration by more than 50 °C.

4. Receiver Characteristics

Essential characteristics of the receiver are summarized in Table 2. It will be observed that the achieved noise figure of less than 10 dB is much less than that for the comparable commercially available receivers characterized by the noise figure over 14 dB, their bandwidth being at least twice as smaller (see e.g. model WBR-0518-MOD from Herley, or model DC-0.5/18G from MITEQ, or RC-5800/5850 from Rockwell Collins).

Next, the described receiver outperforms considerably the aforesaid receivers in term of residual spurious response (–80 dBm against –60 dBm or even higher).

Table 2. **Receiver parameters**

Input frequency range	0.5–19.5 GHz
Bandwidth WB channel	 1100 MHz
NB channel	40, 20, 10 MHz (switchable)
Noise figure at maximum gain	< 10 dB
Gain regulation range WB channel	 15–30 dB
NB channel	15–40 dB
Gain regulation step	1 dB
Frequency tuning step WB channel	 100 MHz
NB channel	1 kHz
Frequency tuning time WB channel	 < 10 msec
NB channel	< 10 μsec
Residual phase noise @10 Hz	 < –55 dBc
@100 Hz	< –75 dBc
@1 kHz	< –95 dBc
@10 kHz	< –105 dBc
@100 kHz	< –115 dBc
@1 MHz	< –120 dBc
Input compression point at 15 dB gain	> 0 dBm
Input IP3 15 dB gain, –10 dBm input signal	 > 10 dBm
30 dB gain, –20 dBm input signal	> –3 dBm
SFDR at –30 dBm input signal and 30 dB gain	60 dB
Residual spurious response at 30 dB gain	< –80 dBm
Operating temperature range	0 to 50 °C
Dimensions	19", 6U module

An extremely low phase noise of local oscillators, being –55 dBc/Hz and –105 dBc/Hz for offsets 10 Hz and 10 kHz, respectively, facilitates performing accurate spectral measurements.

A rather short tuning time, along with the ultrawide instantaneous bandwidth, makes the receiver very suitable for agile continuous monitoring of the whole specified frequency range.

5. Conclusions

A recently developed wideband receiver is described. It is characterized by a low noise figure, an ultrawide instantaneous bandwidth of 1100 MHz, a high dynamical range, a low level of internally created spurious signals, and a low residual phase noise, too. A wide usage of modern MMICs and commercially available on-stock integrated microwave assemblies have allowed to reduce the receiver development time and its cost. Since the receiver does not include tunable YIG filters, there is much room to increase the frequency switching speed and put virtually no bandwidth limitation. The built-in calibration circuits ensure accurate measurements of signal strength over the temperature range of $0-50$ °C.

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ВЫСОКОЧУВСТВИТЕЛЬНЫЙ ПРИЕМНИК ДИАПАЗОНА ЧАСТОТ 0.5–19.5 ГГЦ С МГНОВЕННОЙ ПОЛОСОЙ ПРИЕМА 1.1 ГГЦ

Описывается широкополосный высокочувствительный сверхвысокочастотный приемник, способный принимать сигналы в диапазоне $0.5 \div 19$ ГГц с мгновенной полосой 1.1 ГГц. Приемник имеет коэффициент шума не превышающий 10 дБ и точку интермодуляции 3-го порядка по входу, достигающую +10 дБм. Приемник отличается также малым уровнем внутренних паразитных сигналов и крайне низкими значениями внутренних фазовых шумов. Приведены и обсуждаются основные принципы построения приемника.

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Описується широкосмуговий високочутливий надвисокочастотний приймач сигналів у діапазоні $0.5 \div 19$ ГГц з миттєвою смугою 1.1 ГГц. Приймач має коефіцієнт шуму не вище 10 дБ та точку інтермодуляції 3-го порядку на вході, що досягає +10 дБм. Приймач характеризується також малим рівнем внутрішніх паразитних сигналів та вкрай низькими фазовими шумами. Наводяться та дискутуються основні принципи побудови приймача.

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