Computing, Telecommunication and Control, 2024, Vol. 17, No. 3, Pp. 114–123.
Информатика, телекоммуникации и управление. 2024. Том 17, № 3. С. 114–123.

Circuits and Systems for Receiving, Transmitting, and Signal Processing

Устройства и системы передачи, приема и обработки сигналов

Research article
DOI: https://doi.org/10.18721/JCSTCS.17311
UDC 621.372.543

MONOLITHIC INTEGRATED CIRCUIT OF A FOUR-CHANNEL SWITCHED FILTER BANK FOR THE CENTIMETER BAND BASED ON GaAs pHEMT TECHNOLOGY

D.V. Klimenko[1], *A.B. Nikitin*[2] ✉, *A.A. Stroganov*[2]

[1] Special Technological Center, Ltd., St. Petersburg, Russian Federation;
[2] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation

✉ nikitin@mail.spbstu.ru

Abstract. This article presents the results of the design of a four-channel switched filter bank for the centimeter band manufactured as a monolithic microwave integrated circuit based on domestic GaAs pHEMT technology. The switched filter bank includes a set of bandpass filters operating in four sub-bands of most of the C-, X- and Ku-bands, as well as broadband SP4T switches. The bandpass filters of the lower sub-bands are designed using lumped elements, and higher sub-bands filters are designed using microstrip hairpin resonators. The SP4T switch is based on SPST switches, each of which contains one series- and three parallel-connected field-effect transistors. The switched filter bank has following parameters: insertion losses of no more than 10.8 dB, stopband suppression of at least 43 dB at 30% offset or more from the passband center frequency, and a voltage standing wave ratio of no more than 1.8 in the passband.

Keywords: MMIC, switched filter bank, bandpass filter, SP4T, GaAs pHEMT

Acknowledgements: Production of the integrated circuit was carried out at the expense of the Ministry of Science and Higher Education of Russia within the framework of the federal project “Preparation of personnel and scientific foundation for the electronics industry” under the state assignment for the research work “Development of a methodology for prototyping of electronic component base at domestic microelectronic production facilities on the basis of MPW service” (FSMR-2023-0008).

Citation: Klimenko D.V., Nikitin A.B., Stroganov A.A. Monolithic integrated circuit of a four-channel switched filter bank for the centimeter band based on GaAs pHEMT technology. Computing, Telecommunications and Control, 2024, Vol. 17, No. 3, Pp. 114–123. DOI: 10.18721/JCSTCS.17311

Научная статья
DOI: https://doi.org/10.18721/JCSTCS.17311
УДК 621.372.543

МОНОЛИТНАЯ ИНТЕГРАЛЬНАЯ СХЕМА ЧЕТЫРЕХКАНАЛЬНОГО ПЕРЕКЛЮЧАЕМОГО БАНКА ФИЛЬТРОВ САНТИМЕТРОВОГО ДИАПАЗОНА НА ОСНОВЕ GaAs pHEMT-ТЕХНОЛОГИИ

Д.В. Клименко[1], *А.Б. Никитин*[1] ✉ , *А.А. Строганов*[2]

[1] ООО «Специальный технологический центр»,
Санкт-Петербург, Российская Федерация;

[2] Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Российская Федерация

✉ nikitin@mail.spbstu.ru

Аннотация. В данной статье представлены результаты разработки четырехканального переключаемого банка фильтров сантиметрового диапазона частот, реализованного в виде СВЧ монолитной интегральной схемы на основе отечественной GaAs pHEMT технологии. Переключаемый банк фильтров включает в себя набор из четырех полосовых фильтров, работающих в большей части C-, X- и Ku-диапазонов, а также широкополосные SP4T коммутаторы. Полосовые фильтры низших поддиапазонов выполнены на основе сосредоточенных LC-элементов, а фильтры высокочастотной области – на микрополосковых шпилечных резонаторах. Переключатель SP4T построен на основе SPST переключателей, каждый из которых содержит один последовательно и три параллельно включенных полевых транзистора. Переключаемый банк фильтров имеет вносимые потери не более 10,8 дБ, подавление в полосе заграждения не менее 43 дБ при отстройках от центральной частоты не менее чем на ±30% и коэффициент стоячей волны по напряжению входа и выхода не более 1,8.

Ключевые слова: СВЧ монолитная интегральная схема, переключаемый банк фильтров, полосовой фильтр, SP4T-переключатель, GaAs pHEMT

Финансирование: Производство интегральной микросхемы было выполнено за счет средств Министерства науки и высшего образования России в рамках федерального проекта «Подготовка кадров и научного фундамента для электронной промышленности» по гос. заданию на выполнение научно-исследовательской работы «Разработка методики прототипирования электронной компонентной базы на отечественных микроэлектронных производствах на основе сервиса MPW» (FSMR-2023-0008).

Для цитирования: Klimenko D.V., Nikitin A.B., Stroganov A.A. Monolithic integrated circuit of a four-channel switched filter bank for the centimeter band based on GaAs pHEMT technology // Computing, Telecommunications and Control. 2024. Т. 17, № 3. С. 114–123. DOI: 10.18721/JCSTCS.17311

Introduction

A switched filter bank is a key part of the front-end module in broadband transceivers for various purposes. The main task of the switched filter bank is to suppress unwanted interferences, which depends mostly on the frequency characteristics of the bandpass filters. For the microwave range, the choice is between filters on microstrip structures (interdigital, hairpin etc.) and on LC-elements [1].

A centimeter band switched filter bank can be designed using monolithic integrated circuit technology [2–6], or printed circuit boards [7–10].

In the switched filter bank, the frequency sub-band selection is carried out using solid-state microwave switches [11–14]. These switches can be implemented on the basis of transistor [2, 5, 7] and pin-diodes [4, 8, 9, 11]. A widely used structure of the switched N-channel filter bank is a combination of N filters connected to two SPNT switches located at the input and output of a device [2, 4, 5, 7–10]. Along with this structure, schemes are used, in which switching and filtering functions are combined in one cascade. This solution makes it possible to reduce the size of a monolithic microwave integrated circuit (MMIC) by eliminating the input and output switches of SPNT [3, 6].

The switched filter banks often play a significant role in determining the final frequency characteristics, dimensions and cost for many radio systems. Therefore, the implementation of such a device in the form of MMIC allows to solve the problem of reducing dimensions and increasing reliability of the final product in comparison with a hybrid implementation. A significant number of works are devoted to the design of switched filter bank MMICs. But despite this, the devices considered in them, for the most part, do not fully meet the requirements for Russian radio system manufacturers: significantly different operating frequency bands, bandwidths of channel filters [2, 3, 5, 8, 9] or technology used for MMIC manufacturing [4, 6, 7, 10].

Taking this circumstance into account, as well as restrictions on the supply of imported electronic devices and components to Russia, the task of the centimeter band switched filter bank design becomes more relevant [15].

This paper considers the issues of the four-channel switched filter bank design. The studied MMIC covers C-, X- and Ku-bands. It was designed based on the domestic GaAs pHEMT technology using complex design tools for solid-state microwave devices for the 0.5 μm technological process (PDK_pHEMT05D) [16, 17].

Bandpass filters

The studied switched filter bank contains four channels with filters operating in different frequency sub-bands: No. 1 – 6 GHz ... 8 GHz, No. 2 – 7.5 GHz ... 11.4 GHz, No. 3 – 11 GHz ... 15 GHz, No. 4 – 14.5 GHz ... 18 GHz. The maximum allowed insertion loss level was determined for each bandpass filter: No.1 – 6 dB, No. 2 – 5 dB, No. 3 – 5 dB, No. 4 – 4 dB. Also, all filters must ensure VSWR in the operating frequency band no more than 1.6 and at least 45 dB stopband suppression at 30% offset or more from the passband center frequency.

A comparative analysis of various options for bandpass filters design has shown that for the considered sub-bands, in order to achieve the best frequency characteristics, it is advisable to use different types of filters: filters on lumped elements for lower sub-bands, and filters on distributed elements for higher sub-bands. The use of filters on microstrip structures for low sub-bands leads to a significant increase in the size of the circuits. The conducted studies have shown that it is easier for filters on elements with distributed parameters to ensure the required level of insertion loss in a given frequency band. It should also be noted that such filters are less sensitive to technological deviation of parameters than filters made on LC-elements.

The bandpass filters under study were designed on the basis of MMIC filters from [18]. These bandpass filters were optimized during the design of the switched filter bank. As shown in Fig. 1, CLC-resonators have simplified the design due to the absence of the need to use matching circuits. Thus, it was possible to reduce the area of filter No. 1 from 3.2 mm^2 to 2.7 mm^2 and filter No. 2 from 2.9 mm^2 to 2.4 mm^2. These changes did not affect the performance of the circuit: stopband suppression at 30% offset or more from the passband center frequency is more than 49 dB, VSWR is no more than 1.6 in the passband. Fig. 2 shows a response comparison of the bandpass filters based on LC-resonators with matching circuits and CLC-resonators without matching circuits for sub-bands No. 1 and No. 2. All results were obtained on the basis of electromagnetic analysis using the 0.5 μm GaAs pHEMT PDK.

SP4T switch

To switch between filter bank channels, a broadband single-pole four-throw switch (SP4T) was designed. For the considered SP4T switch, the following parameters were determined: the operating *a*) *b*)

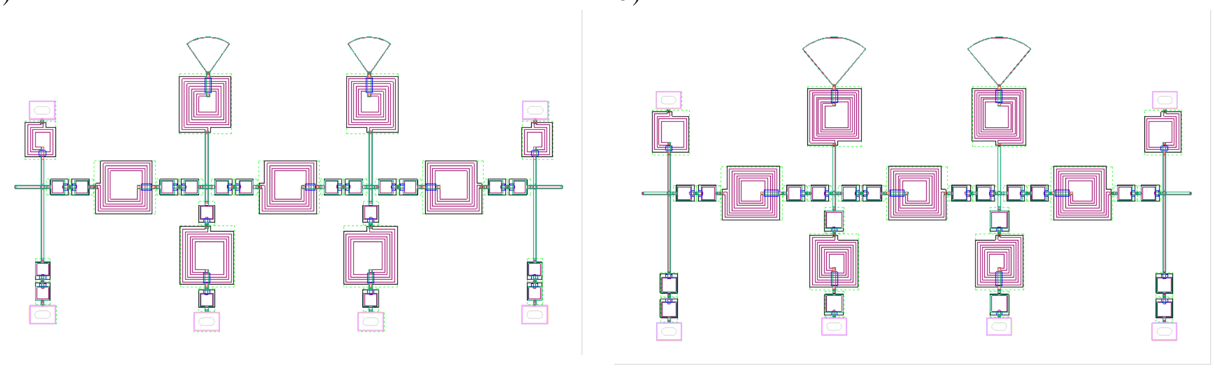

Fig. 1. MMIC layouts of optimized bandpass filters No. 1 (*a*) and No. 2 (*b*)

a) *b*)

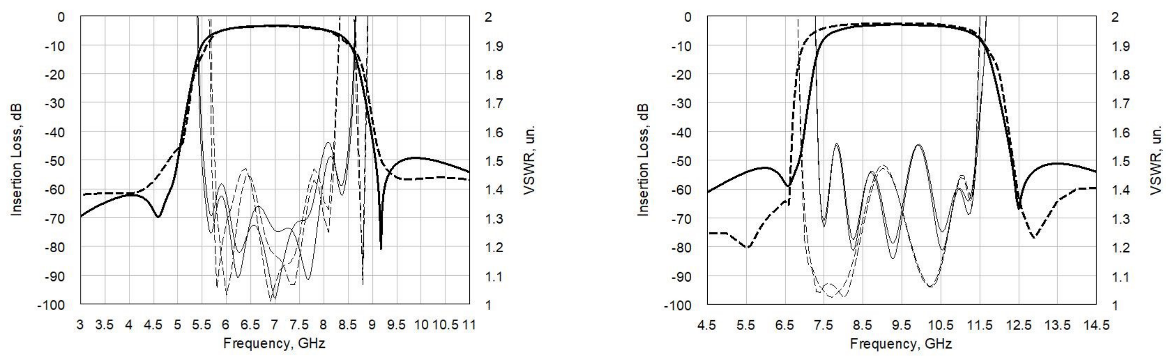

Fig. 2. Frequency responses of bandpass filter No. 1 (*a*) and No. 2 (*b*) with LC resonators and matching circuits (solid line) and CLC-resonators without matching circuits (dashed line)

frequency band is 6 ... 18 GHz, open channel insertion losses are no more than 3 dB, insertion losses and isolation of closed channels are no less than 30 dB, input and output VSWR of open channels is no more than 1.6.

This switch is designed on the basis of three single-pole two-throw switches (SPDT), each of which contains one series-connected field-effect transistor and three parallel-connected field-effect transistors in each channel. A simplified equivalent scheme of a single SPDT channel is shown in Fig. 3.

To increase the isolation between closed channels, it was decided to add an inductor coil to each channel between parallel-connected field-effect transistors. The frequency characteristics are improved due to the parallel resonance between the inductor and the capacitances of the connected in parallel switched-off transistors. As a result, the resistance of the transistor increases in the closed state. When the channel is closed, the inductor coil is shunted by a small resistance of an open transistor connected in parallel [19].

A series-connected inductor coil has been added to the input of the SP4T switch for 50-ohm matching. Since the SP4T switch is used at the input and output of the switched filter bank, a series-connected capacitor was added to ensure DC isolation with other devices.

The results of SP4T switch electromagnetic simulation are shown in Fig. 4, a. The numbers on the graph indicate insertion losses (1) and decoupling (2) in various operation modes of the switches.

The simulation showed that in the entire frequency band, the insertion losses of open channels is no more than 2.6 dB, the insertion losses of closed channels are no less than 37 dB, and the isolation

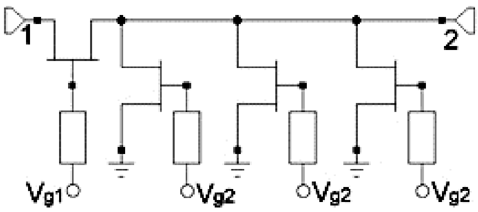

Fig. 3. Simplified equivalent scheme of single SPDT channel

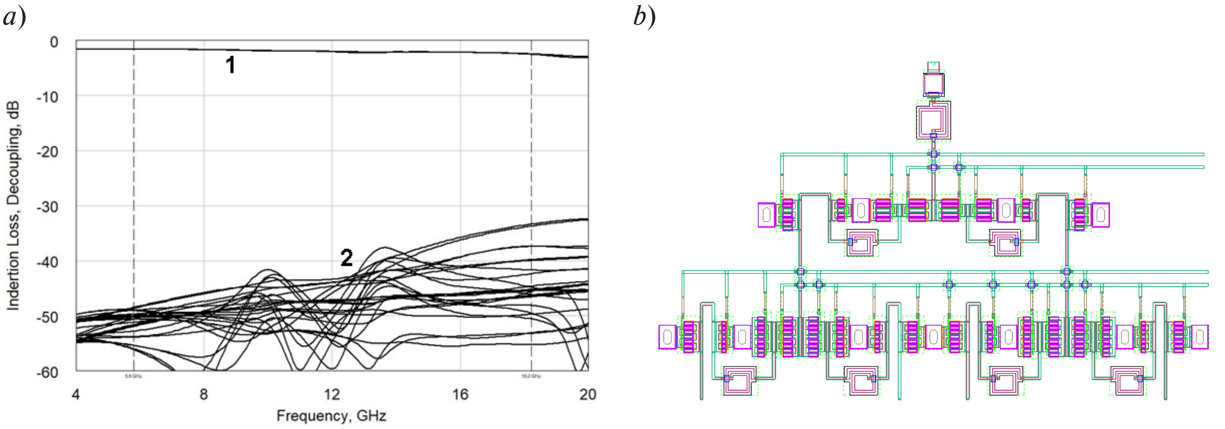

Fig. 4. Frequency responses of SP4T switch (*a*), layout of SP4T switch (*b*)

between closed channels is no less than 33 dB. The input and output VSWR of open channels in all frequency sub-bands is no more than 1.5. It should be noted that the isolation between closed channels in the switched bank filter increases by the amount of bandpass filters loss. Fig. 4b shows the layout of the SP4T switch. The dimensions are 2.3x1.4 mm.

Because the SP4T switch consists of three SPDT switches and each of them requires two control signals to select an output, six control signals are needed to switch between one of the four channels. However, in this work, the switching between channels is carried out using four control signals. This is possible due to a sufficiently high level of insertion loss of the closed channel of the SPDT switch (no less than 37 dB). In each state of the switched filter bank, one channel of the output SPDT switches is open. However, because one of the channels of the input SPDT switch is closed, the necessary isolation between the outputs of the SP4T switch is provided. To simplify switching by reducing the number of control signals, it is possible to use a control driver.

A comparison of the characteristics of the designed SP4T switch and foreign analogues based on GaAs pHEMT technology is presented in Table 1.

The following parameters are used: $f_1 - f_2$ – minimum and maximum bandwidth frequencies; IL – maximum value of the insertion losses of open channels in the bandwidth; Decoupl. – the minimum value of the insertion losses of closed channels and the isolation between channels in the stopband; VSWR – the maximum value of the input and output VSWR in the bandwidth; Size – MMIC size.

A comparative analysis of the collected data showed that the designed switch surpasses foreign analogues in terms of insertion losses of the open channel and VSWR. In terms of parameters such as decoupling, insertion losses of closed channels and MMIC size, the designed switch is inferior only to MMIC [21]. Thus, the SP4T switch, designed on the basis of domestic GaAs pHEMT technology, demonstrates competitive characteristics.

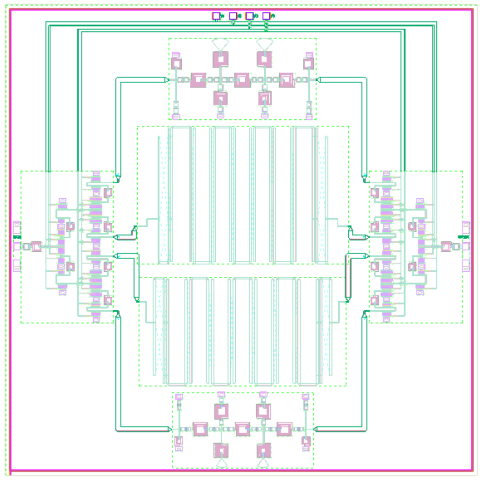

Fig. 5. Switched filter bank layout

Table 1

Characteristics of SP4T switch based on GaAs MMICs

Ref.	$f_1 - f_2$, GHz	IL, dB	Decoupl., dB	VSWR, units	Size, mm²
CMD203C4 [20]	DC-20	≤ 3.1	≥ 22	≤ 2.3	16*
HMC641ALP4E [21]	0.1-20	≤ 2.8	≥ 40	≤ 1.8	3.07
PE42542 [22]	9 kHz – 18	≤ 4	≥ 26	≤ 1.9	16*
This work	6-18	≤ 2.5	≥ 33	≤ 1.45	3.22

*packaged MMIC

Switched filter bank

The final circuit of the switched filter bank consists of two SP4T switches at the input and output and four filters. The layout of the switched filter bank is shown in Fig. 5. The dimensions of the MMIC are 7x7 mm. The filter bank is controlled by four signals supplied to the contact pads located on one side of the MMIC.

50-ohm microstrip lines were used to connect the bandpass filters to the switches. After combining the bandpass filters and switches into a single circuit, the following characteristics were simulated (Fig. 6). Insertion losses are no more than 9.2 dB for channel No. 1, 10.1 dB for channel No. 2, 10.8 dB for channel No. 3 and 10.1 dB for channel No. 4. Stopband suppression at 30% offset or more from the passband center frequency are no less than 50 dB for channel No. 1, 43 dB for channel No. 2, 49 dB for channel No. 3 and 43 dB for channel No. 4. Input and output VSWR in the operating frequency band is no more than 1.6 for channels No. 1 and No. 2, and 1.7 for channels No. 3 and No. 4.

A comparison of the characteristics of the designed switched filter bank and foreign analogues based on GaAs pHEMT technology is presented in Table 2 [23].

The following parameters are used in Table 2: f1 – f2 (FBW) – minimum and maximum bandwidth frequencies (relative bandwidth); IL – the maximum value of the insertion losses of open channels in the bandwidth; Reject. – stopband suppression at 30% offset or more from the passband center frequency; VSWR – maximum value of the input and output VSWR in the passband; Size – MMIC size.

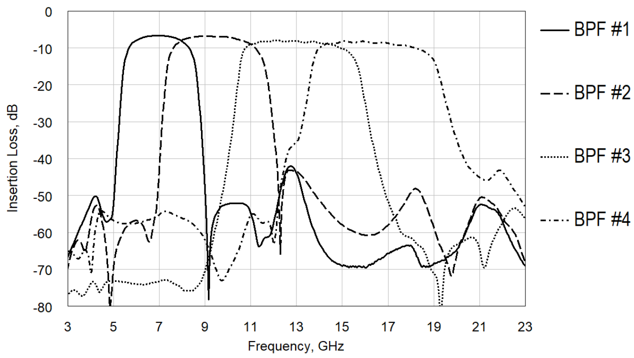

Fig. 6. Frequency responses of switched filter bank channels

Table 2

Characteristics of switched filter bank based on GaAs MMICs

Ref.	$f_1 - f_2$, GHz (FBW %)	IL, dB	Reject., dB	VSWR, units	Size, mm²
BWSBF4-5/18-7C	5–9 (57%)	≤ 11.5	≥ 40	≤ 2	13.5
	8–12 (40%)	≤ 9.5	≥ 40	≤ 2	
	11–15 (31%)	≤ 9	≥ 40	≤ 2	
	14–18 (25%)	≤ 9	≥ 40	≤ 2	
PDSBF-3/20-4	3–5 (50%)	≤ 9	≥ 20	≤ 2	12
	5–8 (46%)	≤ 8.5	≥ 20	≤ 2	
	8–13 (48%)	≤ 9	≥ 20	≤ 2	
	13–20 (44%)	≤ 9.5	≥ 20	≤ 2	
BWSBF5-R8/18-7C8	5–9 (57%)	≤ 10	≥ 40	≤ 1.8	20.25
	8–12 (40%)	≤ 10	≥ 40	≤ 1.8	
	11–15 (31%)	≤ 10	≥ 40	≤ 1.8	
	14–18 (25%)	≤ 9.5	≥ 40	≤ 1.8	
This work	6–8 (29%)	≤ 9.2	≥ 50	≤ 1.6	49
	7.5–11.4 (41%)	≤ 10.1	≥ 43	≤ 1.6	
	11–15 (31%)	≤ 10.8	≥ 49	≤ 1.7	
	14.5–18 (22%)	≤ 10.1	≥ 43	≤ 1.7	

A comparative analysis of the collected data showed that the designed switched filter bank is not inferior to foreign analogues in terms of insertion losses in the bandwidth and surpasses them in terms of stopband suppression and VSWR.

The disadvantage of the designed switched filter bank is its dimensions: the MMIC size is at least twice as large as its analogues. The dimensions of the integrated circuit can be reduced by changing the layout of the SP4T switch. Instead of using three SPDT switches, it is advisable to connect four output paths directly at one point, which will reduce the width of the MMIC. The transformation of the filter structure of sub-bands No. 3 and No. 4 with the transition from microstrip implementation to circuits based on LC-elements can also contribute to reducing the size of the layout. However, as noted above, this may lead to a decrease in the yield of the final product.

One of the options for improvement of the designed switched filter bank is its manufacture in the form of separate MMICs for each subcircuit: switches and filters. The main advantages of a single die are reliability and ease of mounting. The separation of MMIC into individual dies makes it possible to increase the yield of the final product, since if any integrated circuit is out of order, it is enough to replace only this one, and not the entire die. The disadvantages of implementing a switched filter bank in the form of separate filters and switches include additional insertion losses and a decrease in the reliability of the final product due to the use of a greater number of wire connections. In addition, the mounting of the separated switched filter bank MMICs on a printed circuit board is more complicated.

Conclusion

In the course of the work, the switched filter bank was designed, operating in most of the C-, X- and Ku-bands. As a result of the study, the bandpass filters described in the article [18] were modified, the broadband SP4T switch was designed that covers all the necessary sub-bands and surpasses foreign analogues in most of the characteristics considered.

The designed preselector has four sub-bands in the frequency band with a relative bandwidth of 22–41%. In all four states, the switched filter bank has followings parameters: insertion losses are no more than 10.8 dB, input and output VSWR is no more than 1.8 and stopband suppression at 30% offset or more from the passband center frequency is no less than 43 dB. The switched filter bank is designed on the basis of domestic 0.5 μm GaAs pHEMT technology using integrated design tools for solid-state microwave devices.

Possible ways of improvement of the designed switched filter bank were also determined. In particular, options for reducing the size of the MMIC, simplifying the switching of the filter bank, as well as increasing the yield of the final product are proposed.

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INFORMATION ABOUT AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Klimenko Denis V.
Клименко Денис Валерьевич
E-mail: devklimenko@stc-spb.ru

Nikitin Aleksandr B.
Никитин Александр Борисович
E-mail: nikitin@mail.spbstu.ru

Stroganov Alexander A.
Строганов Александр Александрович
E-mail: lemyr103@gmail.com

Submitted: 03.08.2024; Approved: 20.09.2024; Accepted: 27.09.2024.
Поступила: 03.08.2024; Одобрена: 20.09.2024; Принята: 27.09.2024.