SCIENTIFIC BASIS
OF INNOVATION

https://doi.org/10.15407/scine21.02.088

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OPTICALLY CONTROLLED MICROSTRIP SEMICONDUCTOR STRUCTURES

Introduction. *The rapid advancement of information technologies has necessitated updates to hardware components, including the development of high-performance communication devices operating in the microwave frequency range. Among these, frequency-selective devices with controllable characteristics have gained importance.*

Problem Statement. *Existing techniques for controlling frequency-selective devices exhibit several limitations. Mechanical and electromechanical control methods are constrained by low operational speed, bulky design, and high control voltage requirements. Meanwhile, electronic control methods suffer from limited frequency tuning ranges, insufficient decoupling from the control circuit, and complex manufacturing processes. These challenges highlight the need for innovative approaches to circuit design, parameter control, and manufacturing technologies for such devices.*

Purpose. *This study aims to evaluate the feasibility of utilizing optically controlled semiconductor resonant structures for the development of frequency-selective devices.*

Materials and Methods. *Semiconductor materials, such as GaAs and CdS, which exhibit conductivity modulation under laser irradiation at specific wavelengths corresponding to their peak spectral sensitivity, provide a foundation for designing these structures.*

Results. *This research has analyzed methodologies for creating frequency-selective devices with controllable characteristics and introduces a novel implementation strategy. A prototype of a microstrip optically controlled filter using GaAs, operational in the 3–6 GHz frequency range, has been tested. The achieved resonant frequency adjustment was 69 MHz, accounting for 2% of the initial frequency.*

Conclusions. *The study has demonstrated the feasibility of developing optically controlled filters based on semiconductor microstrip structures. The proposed controlled frequency-selective microwave structure can be fabricated using standard planar technology in a single manufacturing cycle, alongside active components.*

Keywords: microstrip semiconductor structures, controllable microstrip filters, optical control, spectral sensitivity of semiconductors, photoconductivity of GaAs.

Citation: Tkachenko, N. S., Didenko, Yu. V., Tatarchuk, D. D., Poplavko, Yu. M., and Oliinyk, O. O. (2025). Optically Controlled Microstrip Semiconductor Structures. *Sci. innov.*, 21(2), 88—92. https://doi.org/10.15407/scine21.02.088

The modern world is inconceivable without information technologies, which have permeated every sphere of human activity. The development of communication technologies has become one of the critical conditions for sustainable societal progress. Consequently, there is a continuous need to upgrade not only information technologies themselves but also their hardware infrastructure. A crucial component of any communication device is various microwave resonant devices, and special attention has been devoted to methods for controlling their characteristics, including operating frequencies and signal phase. Currently, numerous methods for control have been developed:

- mechanical,
- electromechanical,
- electronic,
- combined approaches.

Each of these methods has its advantages and limitations, which determine their areas of application. For instance, frequency-selective devices controlled through mechanical and electromechanical methods have exhibited low speed, relatively large dimensions, and considerable weight. Moreover, the electromechanical method has required relatively high control voltages. Devices employing electronic control have demonstrated a narrower frequency tuning range and, in some cases, introduced parasitic couplings with the control circuit. Additionally, such devices have proven complex to manufacture and calibrate. Existing electronically controlled devices typically rely on semiconductor switching diodes, resulting in a discrete switching mode for operating frequencies.

In light of these drawbacks, the use of optically controlled resonant structures has appeared to be a promising alternative. Microstrip structures have garnered particular interest due to their compatibility with planar technology, small size and weight, absence of electrical coupling between the operating signal and the control circuit, and the capability for smooth frequency control. However, the practical implementation of frequency-selective devices based on such structures has necessitated further research. This study has focused on investigating the feasibility of utilizing optically controlled microstrip resonant structures for the development of frequency-selective devices operating in the microwave range.

The operation of optically controlled microstrip devices relies on two key properties.

First, semiconductor materials at ultra-high frequencies have exhibited sufficiently high dielectric permittivity and a low dielectric loss tangent (see Table), enabling their use as substrates for creating microstrip lines.

Second, the conductivity of semiconductor materials can be modulated by light of a specific frequency. This modulation has allowed changes in the configuration of conductive regions, thereby enabling control over the resonant frequency and phase of the operating signal.

Assuming that the energy distribution of non-equilibrium carriers and their mobility do not differ significantly from equilibrium conditions, the following formula applies:

$$\sigma_f = q\,(\Delta n \mu_n + (\Delta p \mu_p), \qquad (1)$$

where σ_f is the photoconductivity of semiconductor material; q is the charge of electron; Δn, Δp are the non-equilibrium concentrations of light-induced charge carriers; μ_n, μ_p are their mobilities.

In turn, Δn and Δp depend on the intensity and wavelength of the absorbed light. The concentra-

Parameters of Semiconductor Materials in the Microwave Frequency Range at Room Temperature [5]

Material	$\mu_n, \frac{cm^2}{V \cdot s}$	$\mu_p, \frac{cm^2}{V \cdot s}$	ε
CdS	340	110	5.23/5.29
CdSe	720	75	–
ZnS	140	5	–
GaAs	9500	450	10.86
Ge	3900	1900	15.8
Si	1400	500	11.8
AlAs	280	–	–
GaP	190	120	–
SiC	330	600	6.7

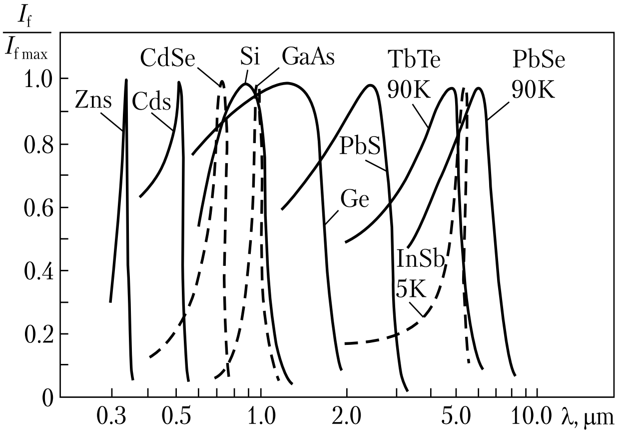

Fig. 1. The spectral sensitivity of the most common semiconductor materials [6]

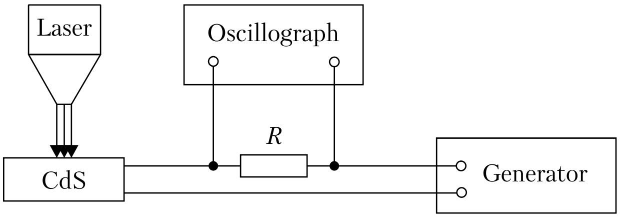

Fig. 2. The schematic of the experimental setup for optical formation of conductive regions on the surface of a semiconductor material

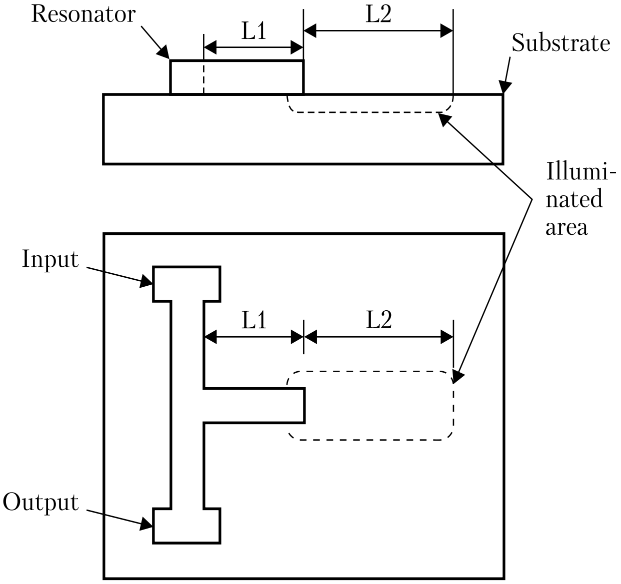

Fig. 3. Microstrip filter based on a half-wavelength resonator

tion of excess charge carriers in the steady state can be determined as follows:

$$\Delta n = \beta\alpha N \tau_n,$$
$$\Delta p = \beta\alpha N \tau_p, \qquad (2)$$

where α is the absorption coefficient of the semiconductor material; N is the number of photons incident on a unit surface per unit time; β is the quantum yield or photoionization coefficient; τ_n, τ_p are the time of relaxation of the carriers. Thus, photoconductivity depends on the illumination intensity and the parameters of the semiconductor. The parameters of certain semiconductors are presented in Table.

It can be shown that photoconductivity is inversely proportional to the frequency of the controlling light flux, which is associated with the varying spectral sensitivity of materials (Fig. 1).

Therefore, an important consideration is selecting a light source suitable for a specific material. Semiconductor lasers or light-emitting diodes (LEDs) can be used as sources of light radiation.

The authors of this work, in collaboration with Prof. B. A. Tsyganko, have conducted studies on the possibility of optically forming conductive regions suitable for transmitting informational signals. These regions have been utilized to develop controllable frequency-selective devices with variable configurations of conductive regions in the microstrip line achieved through optical means. The experimental setup is shown in Fig. 2.

For the experimental study, substrates made of polycrystalline CdS and polycrystalline CdTe were used, with their surfaces illuminated by green and red lasers, respectively. Conductive tracks were formed using the light flux, with the maximum length reaching 5 millimeters and the minimum length being 0.1 millimeters. Sinusoidal signals of varying frequencies were passed through the conductive tracks formed in this way. The maximum signal frequency reached 15 MHz. At higher frequencies, significant signal distortion occurred. The cause of this distortion, in our opinion, is the low carrier mobility in the studied semiconductors (see Table).

A significantly higher signal transmission frequency can be achieved by using GaAs as a substrate, since this material has a high carrier mobility (see Table), sufficiently high dielectric permittivity (which allows for smaller filter element sizes), and low losses in the microwave range. Additionally, GaAs is a technologically established material, enabling the use of standard technological processes for manufacturing devices based on it. In the case of using GaAs as the emission source, it is advisable to use an infrared laser, whose wavelength is well matched to the spectral sensitivity of GaAs (see Fig. 1). Therefore, for further studies, gallium arsenide is used.

On a $20 \times 10 \times 0.4$ mm^3 substrate made of undoped gallium arsenide, a half-wavelength microstrip resonator is fabricated, which is electrically connected to a 50-ohm base line (Fig. 3). An infrared laser is used to form the conductive region near the free end of the resonator, which leads to an extension of the conductive region and, accordingly, a decrease in the resonant frequency. This method results in shifting the resonant frequency of the sample by 2% (almost 69 MHz). The study is conducted in the frequency range from 3 to 6 GHz. In the absence of illumination, the resonant frequency is 3.43 GHz, corresponding to a resonator length of $3\lambda/2$ (where λ is the wavelength of the illuminating radiation). The quality factor is 240. There are theoretical grounds to guess that using a resonator of length $\lambda/2$ can result in a larger frequency shift. A larger frequency shift could also be achieved in the higher frequency range, as the maximum relative size of the effectively illuminated area would be greater in percentage compared to the base resonator. Furthermore, theoretical calculations have shown that based on this resonant structure, a phase shift greater than π radians can be achieved, indicating the potential of this approach and the need for further research.

Thus, the study presents a new approach to the creation of optically controlled frequency-selective devices in the microwave frequency range. The resonant frequency of the filter is controlled by utilizing the dependence of the conductivity of the semiconductor substrate material on the intensity of its illumination.

Based on this approach, a prototype microstrip microwave filter on a substrate made of undoped gallium arsenide has been designed. The dimensions of the substrate are $20 \times 10 \times 0.4$ mm^3. The conductive region is formed near the free end of the resonator using infrared laser radiation, which leads to an effective extension of the resonant structure and, as a result, a decrease in its resonant frequency.

Experimental studies have been conducted in the frequency range from 3 to 6 GHz. In the absence of laser illumination, the resonant frequency of the filter is 3.43 GHz. The quality factor of the resonant structure is 240. Through optical control, a resonant frequency shift of 69 MHz, which corresponds to 2% of the initial value has been achieved.

Therefore, the experimental results have demonstrated the potential of using semiconductor microstrip structures with optical control for the development of a new class of tunable frequency-selective devices in the microwave range. However, to fully realize the potential of this approach, further research is needed to optimize the design of resonant elements and to explore optimal optical control regimes.

REFERENCES

1. Liu, L., Ye, M., Yu, Z. (2020). Ultra-High Peak Rejection All-Optical Microwave Filter Based on the Opto-Mechanical Effect. *IEEE Photonics Technology Letters*, 32(18), 1155—1158. https://doi.org/10.1109/LPT.2020.3013437
2. Tatarchuk, D. D., Poplavko, Y. M., Kazmirenko, V., Borisov, O. V., Didenko, Y. V. (2016). Composites based on dielectric materials for microwave engineering. *Radioelectronics and Communications Systems*, 59(2), 74—82. https://doi.org/10.3103/S0735272716020047
3. Li Liu, Shasha Liao, Wei Xue, Jin Yue. (2020). Tunable all-optical microwave filter with high tuning efficiency. *Optics Express*, 28(5), 6918—6928. https://doi.org/10.1364/OE.384823

4. Li Liu, Xing Liu. (2020). All-optical tunable microwave filter with ultra-high peak rejection and low-power consumption. *Optics Express*, 28(9), 13455—13465. https://doi.org/10.1364/OE.391956
5. Martienssen, W., Warlimont, H. (Eds.) (2005). *Springer Handbook of Condensed Matter and Materials Data*. Spinger Berlin Heidelberg. https://doi.org/10.1007/3-540-30437-1
6. Bube, R. H. (1960). *Photoconductivity of Solids*. John Wiley and Sons, Inc.

Received 19.12.2023
Revised 08.06.2024
Accepted 20.06.2024

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МІКРОСМУЖКОВІ НАПІВПРОВІДНИКОВІ СТРУКТУРИ З ОПТИЧНИМ КЕРУВАННЯМ

Вступ. Розвиток інформаційних технологій потребує оновлення апаратної бази, створення більш ефективних комунікаційних пристроїв мікрохвильового діапазону частот, зокрема й частотноселективних пристроїв з керованими характеристиками.

Проблематика. Існуючі методи керування характеристиками частотноселективних пристроїв мають низку недоліків. Так, пристрої з механічним й електромеханічним керуванням мають низьку швидкодію, габаритні і потребують високих керувальних напруг. Пристрої з електронним керуванням мають невеликий діапазон перелаштування частоти, низький рівень розв'язки зі схемою керування та складну технологію виготовлення. Отже, розробка нових керованих частотноселективних пристроїв потребує принципово інших підходів до схемотехнічних рішень, способів керування робочими параметрами таких пристроїв, технологій їх виготовлення.

Мета. Аналіз можливості використання оптичнокерованих напівпровідникових резонансних структур для створення частотноселективних пристроїв.

Матеріали й методи. Основою для створення таких структур можуть стати напівпровідникові матеріали, наприклад, GaAs або CdS, провідністю яких можна керувати за допомогою лазерного опромінення з довжиною хвилі, що відповідає максимуму спектральної чутливості матеріалів.

Результати. Проаналізовано підходи до створення частотноселективних пристроїв з керованими характеристиками та запропоновано новий підхід до їх реалізації. Протестовано макет мікросмужкового оптичнокерованого фільтру на основі GaAs у діапазоні частот від 3 до 6 ГГц. Значення перелаштування резонансної частоти склало 69 МГц (2% від початкового значення).

Висновки. Показано можливість реалізації оптичнокерованих фільтрів на основі напівпровідникових мікросмужкових ліній, запропоновано конструкцію керованої частотноселективної структури мікрохвильового діапазону. Остання може бути виготовлена за стандартною планарною технологією в єдиному технологічному циклі з активними компонентами.

Ключові слова: мікросмужкові напівпровідникові структури, керовані мікросмужкові фільтри, оптичне керування, спектральна чутливість напівпровідників, фотопровідність GaAs.