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MANIPULATION OF SPATIAL FIELD DISTRIBUTION IN A PLANAR MICROWAVE PHOTON-MAGNON CONVERTER

Subject and Purpose. *The research addresses planar photon-magnon (P-M) converters that efficiently convert between microwave photons and magnons and are essential components in emerging quantum technologies. Planar P-M converters benefit particularly from planar, two-dimensional (2D) resonators. Among them are asterisk-shaped resonators featuring compact geometry and strong concentration of the magnetic component of the electromagnetic (EM) field. The present work seeks an effective approach to optimizing planar P-M converters to enhance conversion efficiency and further miniaturize the device by manipulating the spatial distribution of the high-frequency magnetic field.*

Methods and Methodology. *The proposed approach relies on numerical simulations of the electrodynamic response of the asterisk-shaped resonator coupled to the feeding microstrip line. Families of the resonance spectra are analyzed as a function of the resonator's position relative to the microstrip line, which effectively varies the electromagnetic coupling strength. This methodology allows systematic optimization of the resonator's geometrical and spectral parameters, enabling targeted manipulation of the magnetic field distribution across the magnetic sample location.*

Results. *The conducted analysis has demonstrated that a fine adjustment of the P-M coupling strength can maximize the concentration of the magnetic component of the high-frequency EM field at a desired location within the resonator. Practical recommendations have been developed for designing high-performance planar P-M converters, offering a framework for the efficient integration of asterisk-shaped resonators into miniaturized quantum devices.*

Conclusions. *Based on the numerical analysis of the spectral properties of a 2D asterisk-shaped split-ring resonator (ASRR) intended for a planar microwave P-M converter, it has been shown that selecting the optimal position for the feeding microstrip line allows a high concentration of the magnetic component of the EM field at the resonator center. Proper positioning of the microstrip feeding line is important for achieving a relatively high Q-factor ($Q \approx 200$) for operating modes. The calculated resonance spectra of the investigated P-M converter identify ranges of the resonator offset parameter where dynamic manipulation of the P-M coupling strength is possible and relatively simple.*

Keywords: *microwaves, photon-magnon converter, quantum technologies, asterisk-shaped resonator, coupling strength.*

Introduction

One of the key challenges in advancing quantum technologies is the implementation of photon-magnon (P-M) converters with as high a conversion efficiency as possible. To do this, both conventional-three-dimensional (3D) microwave resonators [1] and planar two-dimensional (2D) resonant struc-

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tures [2, 3] are widely employed. At present, planar structures appear to be particularly promising because their electrodynamic properties are governed by electromagnetic (EM) oscillations predominantly concentrated within the plane of the two-dimensional structure. This offers significant technological advantages, pushing quantum devices toward substantially greater miniaturization.

A particularly bright candidate for use in P-M converters is a class of so-called asterisk-shaped resonators [3—6]. Their advantages primarily arise from the spatial periodicity of the resonator-geometry-forming elements, which allows resonators with dimensions significantly smaller than the operating wavelength, a crucial property for size miniaturization. More importantly, these structures support resonant modes with an extremely high concentration of the magnetic component of the EM field. They are commonly referred to as whispering-gallery modes [4, 7], and their field structure resembles localized surface plasmon-polaritons [8—10].

Despite the established advantages, the practical development and implementation of gainful planar P-M devices are currently hindered by fundamental difficulties arising in analytical EM-field evaluations of 2D resonators and planar electrodynamic structures. As a result, design optimization for geometrical and spectral characteristics is a challenging and computationally intensive task.

The novelty of this work lies in an optimization approach developed for a planar microwave P-M converter based on an asterisk-shaped resonator, aimed at enabling manipulation of the coupling between the feeding microstrip line and various magnetic samples, thereby enhancing the P-M converter efficiency. Specifically, in the proposed approach, families of resonance spectra available from numerical simulations of the resonator's electrodynamic response are studied as a function of the resonator's position relative to the feeding microstrip line (the electromagnetic coupling strength). Using this method, the geometric and spectral parameters of the resonator can be systematically determined and optimized, providing a practical framework for designing high-performance P-M converters.

1. Results and discussion

The resonator structure under investigation is based on an asterisk-shaped split-ring resonator (ASRR) [3] (Fig. 1). The main objective is to optimize the electrodynamic coupling between the ASRR and the feeding microstrip line. Additionally, the feasibility of controlling and tuning the coupling right during physical experiments is also being investigated. A guiding principle for the tuning process is to ensure that the peak of the microwave magnetic field component is precisely at the center of the resonator, which is crucial for achieving high-level microwave P-M coupling [1].

At present, owing to its exceptionally low losses in the microwave and optical frequency bands, yttrium iron garnet (YIG) is the most convenient and widely adopted magnetic material for implementing microwave-optical P-M converters [1]. The development of pioneering magnetic materials (e.g., erbium-doped yttrium iron garnet Er:YIG) goes on [1, 3], opening new opportunities for leading-edge technological devices. The achievable concentration of the microwave magnetic field component is inherently linked to the magnetic material properties. Clearly, the task of optimizing properties is getting increasingly important with each newly developed magnetic material.

The asterisk-shaped SRR/ASRR is based on a split-ring resonator (SRR) with the outer diameter $b = 0.5$ mm and the inner diameter $a = 0.3$ mm (Fig. 1, *a*) [3]. The ASRR structure has nineteen identical sectors (each consisting of a radial metal arm combined with a separating gap) distributed uniformly, with angular cyclicity $\varphi = 360°/38$ along the ring perimeter. These radial metal arms increase the outer (overall) diameter of the structure to $c = 5.2$ mm. To form the ASRR, the radial gap between two neighboring arms is lengthened along the x-axis till it crosses the inner circumference of the ring to split it (Fig. 1, *a*). No more structural discontinuities are required.

The proposed multilayer structure is a five-layer sandwich (Fig. 1, *c*). The top layer is a copper film of thickness $p = 35$ μm and conductivity $\sigma = 60$ MS/m. It produces an asterisk-shaped SRR. Directly beneath it, there is a Rogers RO3010 dielectric substrate of thickness $g = 0.25$ mm, relative permittivity $\varepsilon_r = 11.2$, and loss tangent being $\tan\delta = 0.0022$.

The feeding microstrip line is a 35 μm thick copper film deposited on a dielectric substrate. The microstrip line $d = 1$ mm wide and $e = 20$ mm long is supported by another Rogers RO3010 dielectric sub-

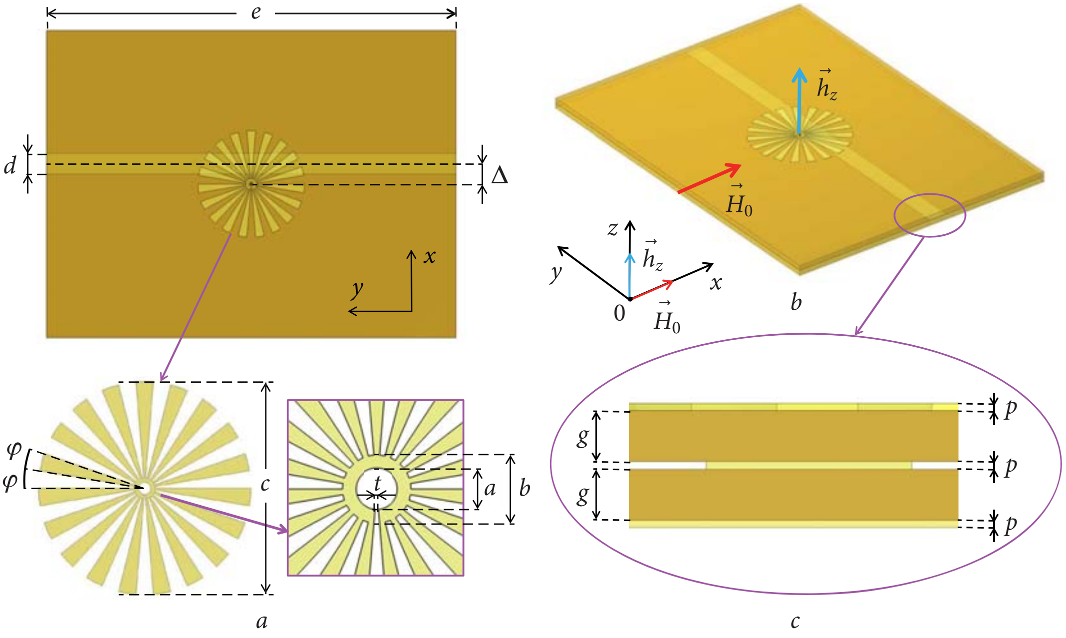

Fig. 1. Asterisk-shaped SRR and its key features: top view indicating the resonator horizontal offset Δ (*a*), isometric view indicating $\vec{H}_0$ and $\vec{h}_z$ directions (*b*), and side view of the multilayer structure (*c*). The ASRR key dimensions: $a = 0.3$ mm, $b = 0.5$ mm, $t = 25$ μm, $c = 5.2$ mm, $\varphi = 360°/38$, $d = 1.0$ mm, $e = 20$ mm, $p = 35$ μm, and $g = 0.25$ mm

strate of thickness $g = 0.25$ mm. The bottom layer is a continuous, $p = 35$ μm thick copper ground plane.

A horizontal, *x*-directed offset, Δ, exists between the SRR geometric center and the central line (or spine) of the microstrip line (Fig. 1, *a*). In this study, Δ is taken to be the primary design parameter. The resonator performance is optimized by varying the offset Δ to control the electromagnetic coupling.

The $\vec{h}_z$-marked arrow in Fig. 1, *b* shows the direction of the out-of-plane AC magnetic component of the EM field localized on the ASRR. The present study focuses on the h_z component because it governs the magnetic resonance behavior of the ASRR. The external static magnetic field, $\vec{H}_0$, is not included in this analysis but reserved for future work.

Before analyzing the spectral and field characteristics of the investigated structure, the microwave coupling between the feeding microstrip line and the ASRR should be optimized. For this, the transmission coefficient (parameter $|S_{21}|$) versus frequency is numerically analyzed at different microstrip line widths *d* and under weak-coupling conditions. According to the obtained results, the coupling is optimum from $d = 1.0$ to 1.2 mm. At those *d* widths and in the operating frequency band, the resonance $|S_{21}|$ value varies slightly (Fig. 2).

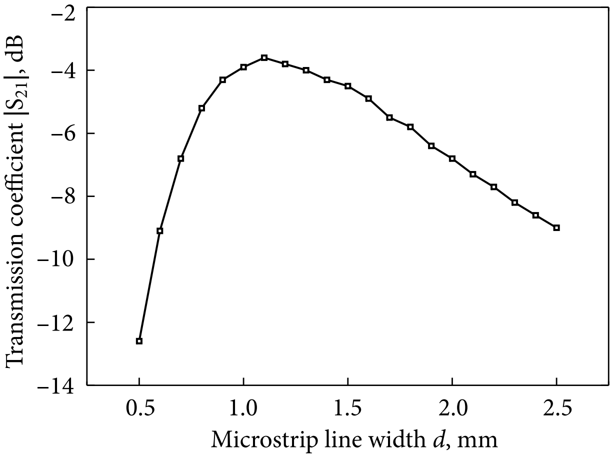

Fig. 2. The microstrip line width optimization: resonance $|S_{21}|$ value versus microstrip line width

Now let us proceed to the obtained results and analyse in detail the resonance spectra of the ASRR as part of the microwave P-M converter.

A sample of the studied-structure spectra is presented in Fig. 3 as a three-dimensional dependence — a spectral intensity map. Figure 3 shows the spectra of the $|S_{21}|$ transmission coefficient of the studied structure as a function of frequency ($f = 6.0$—10.0 GHz) with the *x*-directed offset Δ varying from −3 to +3 mm.

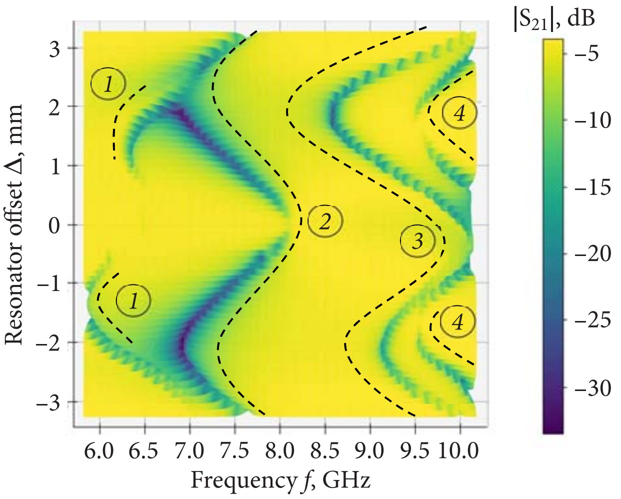

Fig. 3. The spectral intensity map of the $|S_{21}|$ transmission coefficient depending on the resonator offset Δ relative to the spine of the microstrip line

Notice that while Fabry–Pérot resonators admit analytical treatments, the sophisticated geometry of ASRR boundaries requires fully numerical simulations. The spectral properties should be analyzed as functions of the key geometric parameters. Here, in particular, the offset Δ between the microstrip line and the resonator is considered for this purpose.

The $|S_{21}|$ spectra (i.e., the resonance peak profiles) identified in those regions yield almost symmetric and periodic graphical representations with respect to $\Delta = 0$ mm. The observed asymmetry arises from the inherently asymmetric (relative to the microstrip line) split design of the ASRR, which changes the induced current distribution and, hence, the coupling characteristics.

Two most pronounced mode families (#1 and #2) and (#3 and #4) are distinguished in the obtained spectra. We restrict ourselves to the analysis of two representative modes #1 and #2 because their field distributions align more closely with our study objectives.

For mode #2, the characteristic quality factors range from 6 to 40, which is typical for the microwave resonators used in P-M converters. In contrast, the quality factors of mode #1 span a broader range, 35 to 200. However, the corresponding resonance amplitudes of mode #1 are approximately 2 to 4 times lower than those of mode #2.

Importantly, despite its lower resonance intensity, mode #1 is more practical, for at its resonance frequencies, the h_z component of the AC magnetic field is more strongly localized around the ASRR central aperture. In particular, analyzing the spatial field distributions at the minima of the calculated spectra reveals that within the offset parameter range $\Delta = -2.1$ to -2.9 mm, the h_z component concentration inside the resonator reaches its maximum.

Therefore, this region of the offset parameter for mode #1 is identified as the most suitable operating mode for applications where a strong and spatially uniform localization of the magnetic field is essential.

Let us have a closer look at the $\Delta = -2.1$ to -2.9 mm region. For the investigated structure, the spectra of the resonant oscillations exhibiting the most promise for the assigned tasks are shown in Fig. 4.

According to the spectra in Fig. 4, as the absolute value of the offset parameter Δ increases and mode #1 comes closer to mode #2 in frequency (Fig. 4, *a*, *b*), the qualities of both modes sharply increase. But the quality of mode #1 grows sharper, reaching a score of 200. Simultaneously, an extremely high concentration of the h_z component of the AC magnetic field occurs at the very center of the resonator, the most convenient location of the magnetic sample.

Roughly speaking, the quality factors of both #1 and #2 modes approach their maxima within $\Delta = -2.7$ to -2.8 mm. As Δ grows in magnitude further, the intensity of mode #1 decreases gradually, but not enough to lower the mode coupling strength. This behavior is most likely attributed to that the #1 and #2 mode coupling is optimized precisely within $\Delta = -2.7$ to -2.8 mm.

To gain a definitive characterization of the EM field spatial distributions in the resonator under optimal geometric conditions, the following procedure is adopted. Consider the spatial field distribution in Fig. 5 for the h_z component of the AC magnetic field in the vicinity of the resonator surface. For mode #2, these h_z oscillations arise from the resonance between the microstrip line and the ASRR spatial region lacking a well-defined geometric boundary. In precise terms, the virtual boundary of this oscillation field inside the ASRR holds at approximately half the resonator radius (see Fig. 5, *a*, *b*) for modes #2 and #3. Furthermore, the azimuthal field distribution in a region surrounding the resonator center shows that an integer multiple of a wavelength fits along the resonator circumference.

These #2 and #3 modes have the field structure of whispering gallery modes [10] (dipole for mode #2

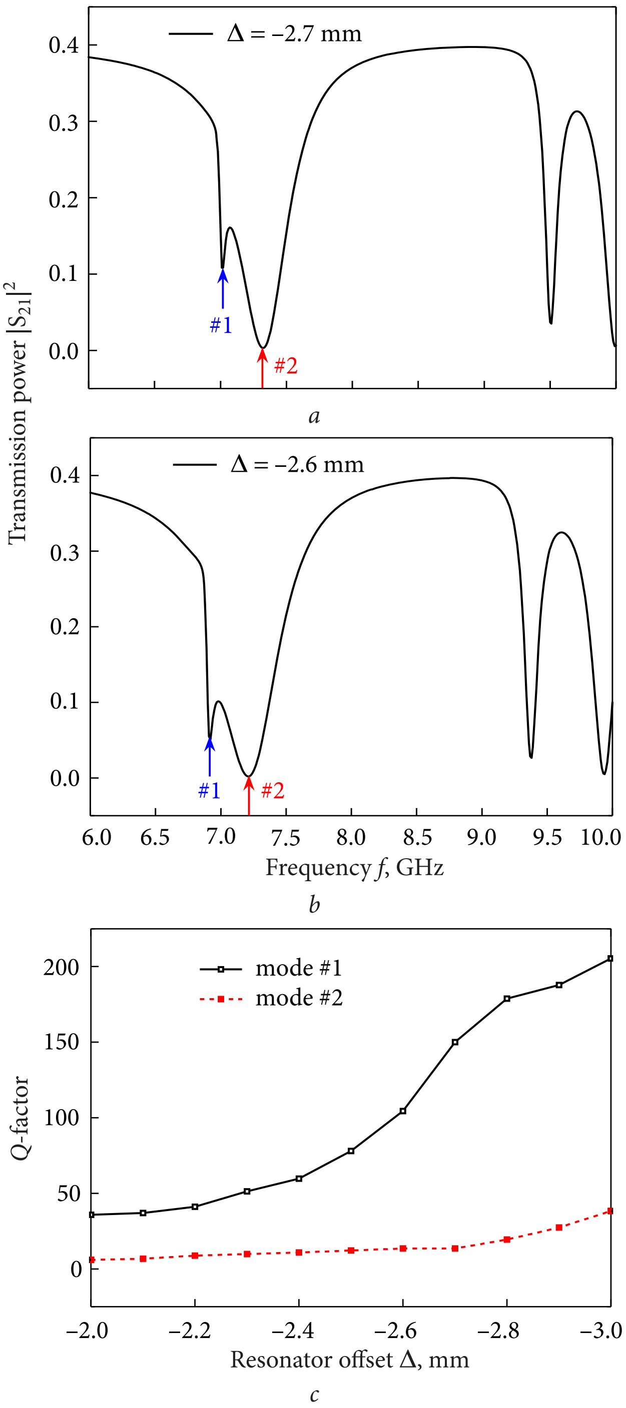

Fig. 4. Characteristics of the most suitable ASRR modes #1 and #2: the ASRR spectra in the #1 and #2 mode coupling region at offset parameters $\Delta = -2.7$ mm (*a*) and $\Delta = -2.6$ mm (*b*), and the quality factor rise driven by the #1 and #2 mode coupling increase with the resonator offset Δ varying (*c*)

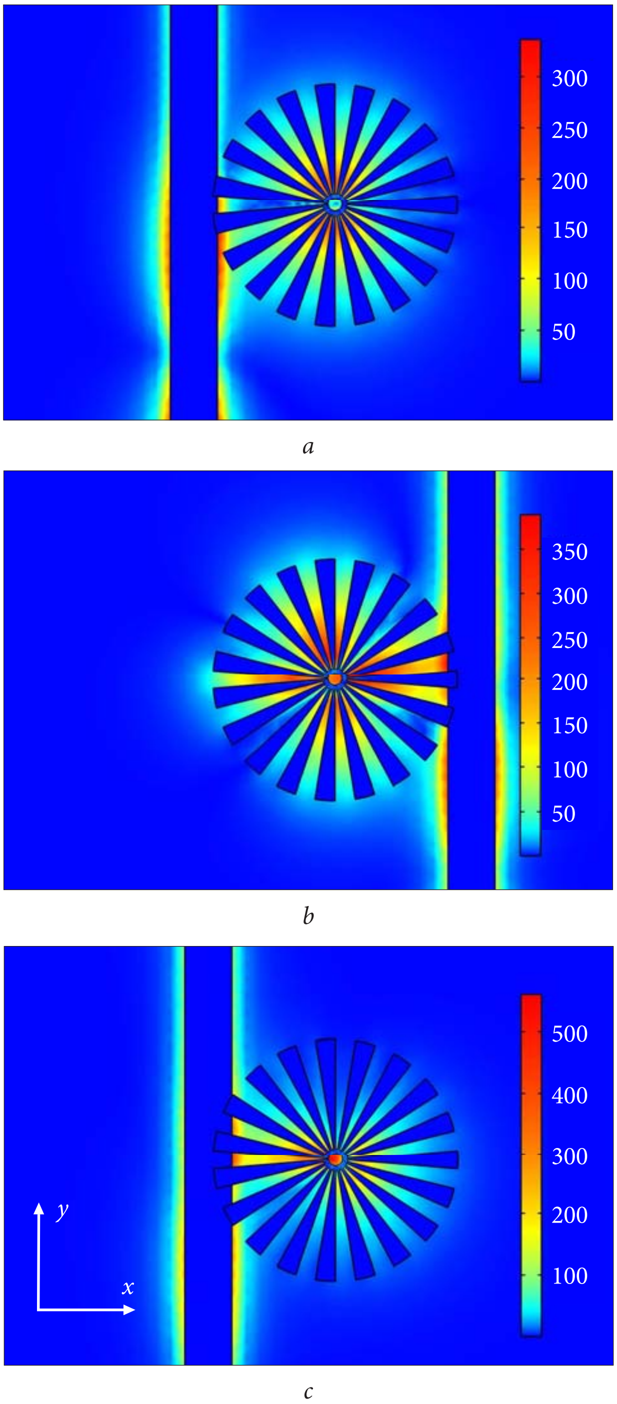

Fig. 5. The spatial field distribution of the $|h_Z|$ component of the EM field: mode #2 at $\Delta = -3.0$ mm, $f = 7.66$ GHz (*a*), mode #3 at $\Delta = +2.9$ mm, $f = 9.86$ GHz (*b*), and mode #1 at $\Delta = -2.7$ mm, $f = 7.01$ GHz (*c*)

and quadrupole for mode #3), which, in turn, correspond to localized surface plasmons.

The oscillations of mode #1 occur due to the resonance between the edge of the microstrip line and the surface of the inner split ring of the ASRR. In this case, the boundary for the resonant oscillation within the ASRR is well defined and aligns precisely with the geometric edge of the inner split ring of the resonator, as shown in Fig. 5, *c*. The azimuthal field distribution corresponds to a half-wavelength along the circumference of the resonator.

Evidently, despite its lower resonance intensity, mode #1 is the most suitable for the operating mode of the microwave P-M converter, reaching its maximum quality factor $Q \approx 200$ in the region of optimal coupling to the feeding microstrip line. In this regime, the magnetic component of the electromagnetic field is strongly spatially confined to the central area of the aste-risk-shaped resonator. Therefore, the ASRR central area is an optimal location for a magnetic sample of yttrium iron garnet (YIG) or erbium-doped YIG (Er: YIG).

It is worth noting that the observed Q-factor increase and the #1 and #2 mode convergence in frequency are likely associated with the formation of a hybrid dark mode for #1 mode [4].

Conclusions

A numerical analysis of the spectral properties of a two-dimensional asterisk-shaped split-ring resonator as part of a planar microwave P-M converter has been performed. From this study, we can reasonably infer that:

- Placing the feeding microstrip line into the optimal position enables a high-level concentration of the magnetic component of the EM field in the resonator's central area.
- Proper positioning of the feeding microstrip line makes it possible to achieve relatively high resonator quality factors, $Q \approx 200$, of the resonator for the operating mode.
- A relevant analysis of the calculated set of the resonance spectra for the investigated P-M converter makes it possible to identify resonator's offset parameter regions in which relatively simple dynamic manipulation of the P-M coupling strength is achievable.

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МАНІПУЛЮВАННЯ ПРОСТОРОВИМ РОЗПОДІЛОМ ПОЛЯ В ПЛАНАРНОМУ МІКРОХВИЛЬОВОМУ ФОТОН-МАГНОННОМУ ПЕРЕТВОРЮВАЧІ

Предмет і мета роботи. Предметом досліджень є планарні фотон-магнонні перетворювачі, які є важливими компонентами сучасних квантових технологій, що забезпечують ефективне перетворення між мікрохвильовими фотонами та магнонами. Ці пристрої особливо виграють від використання планарних двовимірних (2D), зокрема астрископодібних, резонаторів завдяки їхній компактній геометрії та сильній концентрації магнітної складової електромагнітного поля. Метою роботи є розроблення підходу до оптимізації таких планарних фотон-магнонних перетворювачів шляхом керування просторовим розподілом високочастотного магнітного поля, що дозволяє підвищити ефективність перетворення та забезпечити мініатюризацію пристроїв.

Методи та методологія. Запропонований підхід ґрунтується на чисельному моделюванні електродинамічної відповіді астрископодібних резонаторів, з'єднаних із живильними мікросмужковими лініями. Сімейства резонансних спектрів аналізувалися як функція положення резонатора відносно мікросмужкової лінії, що фактично змінює величину електромагнітного зв'язку. Така методологія дозволяє систематично оптимізувати геометричні та спектральні параметри резонатора, забезпечуючи цілеспрямоване керування розподілом магнітного поля в області розташування магнітних елементів.

Результати. Проведений аналіз показує, що точне налаштування сили зв'язку дозволяє досягти максимальної концентрації магнітної складової високочастотного електромагнітного поля у необхідній області резонатора. На основі отриманих результатів сформульовано практичні рекомендації щодо проєктування високоефективних планарних фотон-магнонних перетворювачів, що створює основу для ефективної інтеграції астрископодібних резонаторів у мініатюризовані квантові пристрої.

Висновки. Виконано чисельний аналіз спектральних властивостей двовимірного астрископодібного розщепленого кільцевого резонатора для планарного мікрохвильового фотон-магнонного перетворювача. Результати показують таке: вибір оптимального положення живильної мікросмужкової лінії забезпечує високу ступінь концентрації магнітної складової електромагнітного поля в центрі резонатора; належне розташування живильної мікросмужкової лінії дозволяє реалізувати відносно високі добротності резонатора ($Q \approx 200$) для робочих мод; аналіз розрахованого набору резонансних спектрів для досліджуваного фотон-магнонного перетворювача дозволив визначити області параметра зміщення резонатора, у яких може біти досягнуто відносно просте динамічне керування силою фотон-магнонної взаємодії.

Ключові слова: *мікрохвилі, фотон-магнонний перетворювач, квантові технології, астрископодібний резонатор, величина зв'язку.*