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# ACTIVE INTEGRATED ANTENNAS AND ARRAYS WITH FIELD-EFFECT TRANSISTORS

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Electromagnetic wave generation processes in the hybrid log-periodic microstripe antenna on the dielectric substrate integrated with field-effect transistor are experimentally studied in the frequency range of 6—20 GHz. The possibility of synchronization and power combining in the array consisting of antenna-coupled oscillators placed on the common dielectric substrate is investigated. It is shown that the considerable increasing the generation efficiency and power combining can be obtained by using the external synchronization signal or quasi-optical design of the array.

## Introduction

Active antennas or antenna-oscillators are simple and compact radiators that can be applied in microwave and millimeter wave frequency ranges as elements of the arrays [1, 2]. In these radiating devices, active semiconductor diodes or transistors are integrated with planar antennas. Investigation of generation processes and power combining in active antenna arrays with semiconductor diodes shows the advantages of field-effect transistors in such applications [3]. Using field-effect transistors in these radiators raises a number of problems associated with the dependence of oscillation frequency simultaneously on several factors: transistor impedance and gain, antenna geometry, thickness and dielectric constant of the substrate. Thus, the antenna design optimization is required to obtain desired characteristics essentially for the millimeter wave applications.

In this work, the log-periodic planar antennas with field-effect transistors are studied. Mutual and external synchronization of oscillators in the linear array are used for increasing the generation efficiency and space power combining accuracy. The generation mode variations on the dependences of electrodynamic parameters of the antenna are investigated.

### Log-periodic active antenna

Depending on the antenna-coupled oscillator application, different types of the planar antennas can be used. For the broad frequency band operation, log-periodical antennas are of the interest [4]. Using the dielectric substrate with metalized back side [5] provides the necessary level of the feedback for microwave generation.

The log-periodic active antenna structure which was used in this work is shown in Fig. 1, where $d$ is the substrate thickness; $l$ is the tooth length. This antenna can be represented as a set of the resonant circuits with frequencies equaled to $f_1(\sqrt{2})^n$ [6], where $f_1$ is the antenna fundamental frequency defined by the length of largest tooth; $n = 0,1,2,3,...$ At the fundamental frequency, such radiator has a sufficiently high quality factor exceeding 100 [7].

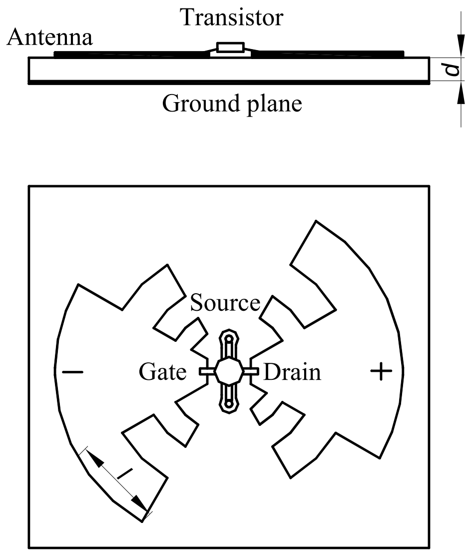



Fig. 1. The structure of active antenna with field-effect transistor.

Both computer modeling and experimental research of the electromagnetic field parameters were utilized to optimize the design and to estimate the prospective of log-periodic antennas application in antenna arrays and power combiners. The radiation pattern of the antenna, its S-parameters and radiated electromagnetic filed density versus dielectric thickness and antenna dimensions were modeled using the 3D transmission line matrix method [8]. This method considers the computational space domain as a mesh of transmission lines interconnected in nodes. In the case of 3-dimentional space, electric and magnetic fields on the sides of the node with numbers $l, m, n$ at time instant $k$ may be summarized in 12-dimensional vectors

$$ {}_kE_{l,m,n} = {}_k\left[E_1, E_2, ..., E_{11}, E_{12}\right]^T_{l,m,n}; $$
$$ {}_kH_{l,m,n} = {}_k\left[H_1, H_2, ..., H_{11}, H_{12}\right]^T_{l,m,n} $$

They can be linked with the incident and scattered amplitude vectors via

$$ {}_ka_{l,m,n} = \frac{1}{2\sqrt{Z_F}}\,{}_kE_{l,m,n} + \frac{\sqrt{Z_F}}{2}\,{}_kH_{l,m,n} $$
$$ {}_kb_{l,m,n} = \frac{1}{2\sqrt{Z_F}}\,{}_kE_{l,m,n} - \frac{\sqrt{Z_F}}{2}\,{}_kH_{l,m,n} $$

where $Z_F = \sqrt{\mu/\varepsilon}$ is the field impedance; ${}_ka_{l,m,n}$ defines the vector of amplitudes of incident waves to the node; ${}_kb_{l,m,n}$ is the vector of the scattered wave amplitudes. The relation between amplitudes of incident and scattered waves is given by the matrix equation

$$ {}_kb_{l,m,n} = S_k a_{l,m,n}, $$

where $S$ is the scattering matrix.

To obtain the initial data for computing the radiation parameters, experiments with the real antenna were performed. During the experiments, the antenna was placed on the rotary platform to measure its radiating power and frequency spectrum. Using these measurement data, the antenna radiation pattern was calculated. The antenna radiation efficiency was investigated in the frequency range of 7.5—22.5 GHz for the different dielectric thickness.

The simulated and measured results are presented in Fig. 2. This figure shows that the value of radiated power significantly depends on the dielectric thickness $d$. It reaches the maximum at $d \approx \lambda_d/4$, where $\lambda_d = \lambda_0/\sqrt{\varepsilon}$ defines the wavelength in the dielectric; $\varepsilon$ denotes the relative permittivity; $\lambda_0$ is the wavelength in free space. The discrepancy between calculated results and experimental data is caused by the approximate calculation of electrodynamic characteristics of the antenna structure without taking into account the possible changes in transistor operation mode.

The signal reflected from the ground plane can be considered as an element of positive feedback. Consequently, the transistor will be placed in the maximum of field strength at the dielectric thickness close to quarter wavelength. This results in higher power output signal radiated by the antenna. When the reflecting plane is absent, the antenna-oscillator is not operating due to a low feedback level.

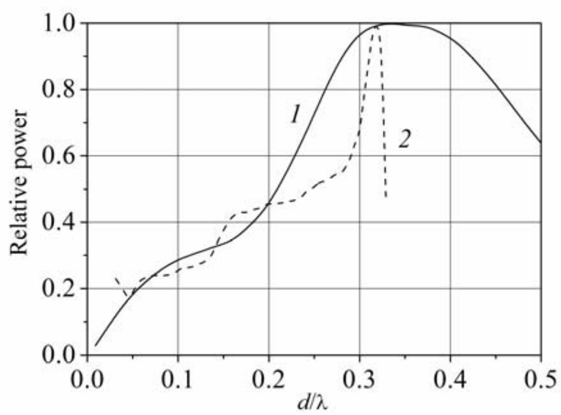



Fig. 2. Radiated power versus normalized substrate thickness: (*1*) calculated curve; (*2*) experimental data.

Oscillation frequencies of the active log-periodic antenna are defined by its teeth lengths. The fundamental frequency is defined by the length of largest tooth $l$ approximately equal to a quarter of the effective wavelength [6]

$$ l \approx \lambda_{eff}/4;\ \lambda_{eff} = \lambda_0/\sqrt{(\varepsilon+1)/2}. $$

This assessment is proved by calculated results and measurement data shown in Fig. 3. The figure shows that the calculated oscillation frequencies of the active antenna are in good agreement with measured results.

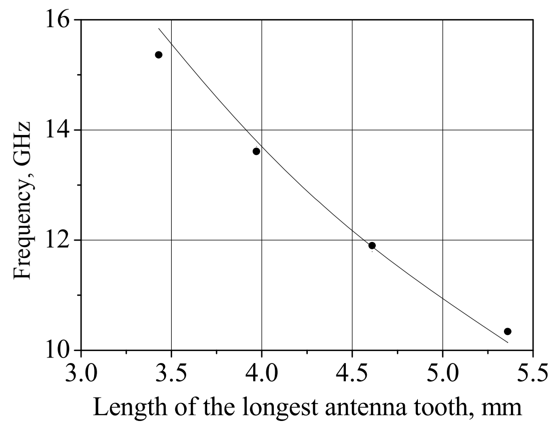



Fig. 3. Oscillation frequencies of the active antenna as a function of its geometrical dimensions: solid curve denotes calculated values; experimental data are depicted by points.

As a multi-resonance system, the log-periodic antenna can operate in multi-frequency mode. Here, the dependence of the transistor gain versus the operating frequency plays the key role. In our research, we have explored the field-effect transistor NE350184C with the gain dependence shown in Fig. 4.

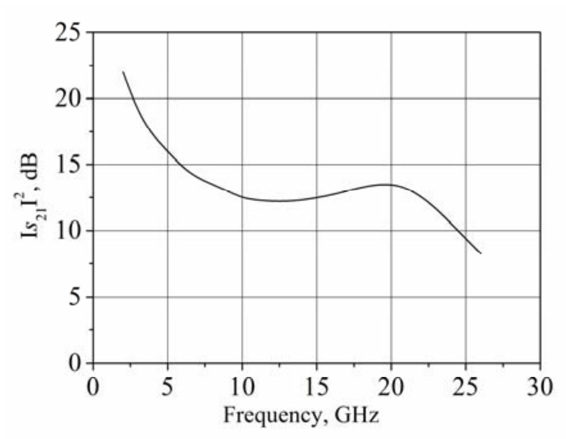



Fig. 4. The gain of the NE350184C field-effect transistor versus operating frequency.

Fig. 5 represents the signal spectrum of the antenna designed on the dielectric substrate with thickness $d = 0.2\lambda_d$ close to quarter wavelength on the fundamental frequency. The measured oscillation frequency is close to the predicted value and is equal to $f_{1c} = 13.7$ GHz.

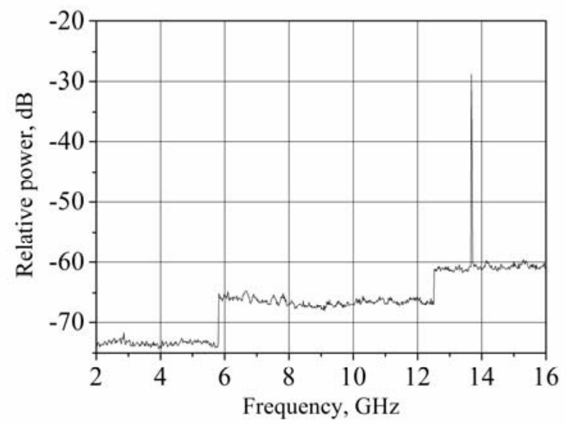



Fig. 5. The radiation spectrum of the active antenna in a single-frequency mode.

In certain cases, the spurious oscillation is observed if the dielectric substrate thickness is approximately equal to the value $d = 0.1\lambda_d$. Fig. 6 shows that the spurious oscillation frequency is almost a half of the fundamental one. As follows from Fig. 4, the transistor gain on the spurious oscillation frequency is much higher than on the fundamental frequency.

For the spurious mode, the resonator is formed by the entire antenna representing the vibrator in which the every next arm is twice longer than the previous one. Besides the high transistor gain, a thin dielectric substrate as compared to the fundamental frequency wavelength is another reason for the spurious signal excitation. In this case, the third harmonic of the spurious signal frequency can be observed as shown in Fig. 6.

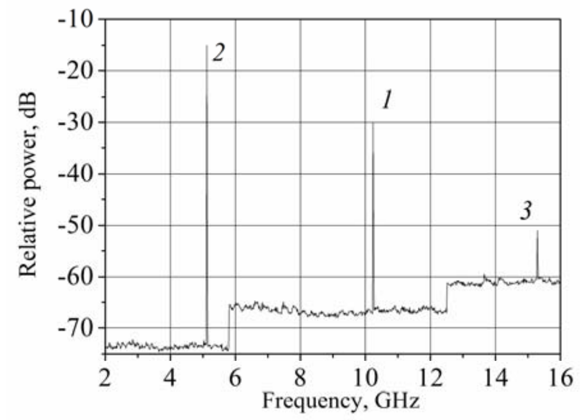



Fig. 6. The radiation spectrum of the active antenna in multi-frequency mode: (*1*) fundamental frequency; (*2*) spurious signal frequency; (*3*) third harmonic frequency of spurious signal.

An antenna tooth with the length approximately equal to one third of the antenna radius is the resonator for this frequency. The presence of the spurious signal harmonics specifies the possibility of quite effective operation of the antenna-oscillator on higher frequency modes.

## Synchronization and space power combining of the active antenna radiation

The active antenna described above can be employed as a radiating element in the quasi-optical array. In this case, it is important to provide the frequency and phase synchronization of the antenna-coupled oscillators disposed on the common dielectric substrate.

The experimental results [9, 10] show that mutual synchronization of the antenna-coupled oscillators is possible, if the discrepancy between their operation frequencies is less than 50 MHz. As a result, the array radiation is realized at the single frequency. Mutual influence of the oscillators occurs mainly due to the excitation of the surface waves in the dielectric substrate. Coherent power combining accompanied by narrowing the total radiation pattern occurs when antennas are placed in line and the distance between their centers is close to the wavelength in dielectric. In contrast to linear array, the two-dimensional array forms the multi-beam radiation pattern since the phase synchronous interaction of all oscillators is not guaranteed despite the frequency synchronization availability. The array irradiation by the external microwave source allows solving the problem of frequency and phase synchronizations for a large number of independent oscillators. To investigate the implementation possibility of frequency and phase synchronizations, the experimental setup shown in Fig. 7 was used. The array irradiation and the output signal indication were performed by horn antennas placed in the far-field zone. Microwave radiation was registered by spectrum analyzer HP 8566A with 100 KHz high frequency resolution.

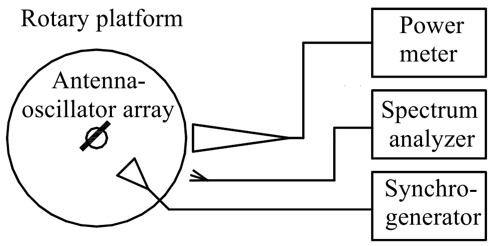



Fig. 7. The equipment setup for experimental investigating the synchronization of active antennas by external electromagnetic field.

Under the irradiation by external signal, the antenna-oscillator generation frequency can be changed in the limits up to 400 MHz [11]. The external power necessary to synchronize one antenna-oscillator is ten times less than its output power.

In the case of mutually synchronized active antennas, the frequency range of the external signal, in which the synchronization occurs at the operation frequency of external oscillator, depends on the number of antenna-oscillators in the array and the intensity of the external irradiation as illustrated in Fig. 8. As follows from this figure, increasing the number of simultaneously operating active antennas leads to decreasing the band of their synchronization by external signal. The synchronization band monotonically grows with the increase of the power flow density of electromagnetic field affected the antenna-oscillator array.

In the case of simultaneous operation of several independent antenna-oscillators in the array, their external synchronization is possible under following factors. The most important factors are number of operating active antenna-oscillators, discrepancy of their own frequencies and intensity of the external irradiation. In the linear array consisting of three antenna-oscillators, the synchronization by external irradiation with intensity 300 $\mu W/cm^2$ can be achieved if the discrepancy of antenna-oscillator frequencies is near 150 MHz that is three times more than in the case of mutual synchronization without external signal.

Fig. 9 shows the spectrum evolution of the linear array radiation under synchronization by external signal. In the absence of external signal, the asynchronous multi-frequency mode operation illustrated by Fig. 9*a* is due to the mutual influence of radiating antenna-oscillators. Under influence of the external signal at the frequency located out of the synchronization band, the mutual synchronization is observed.

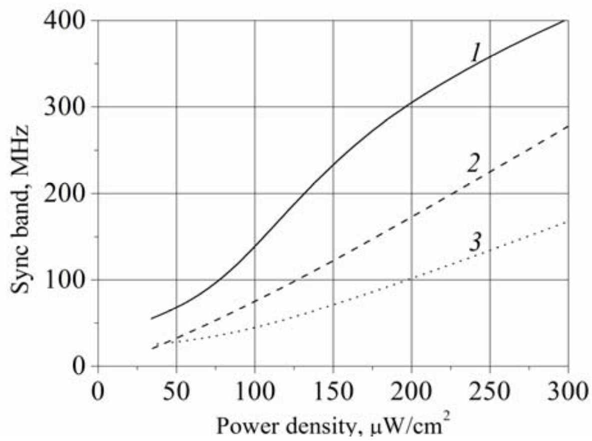
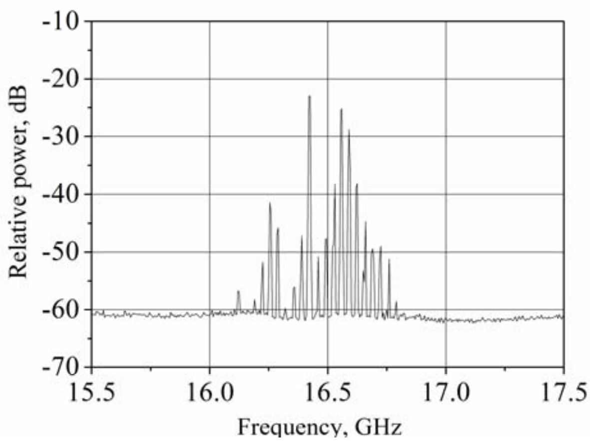
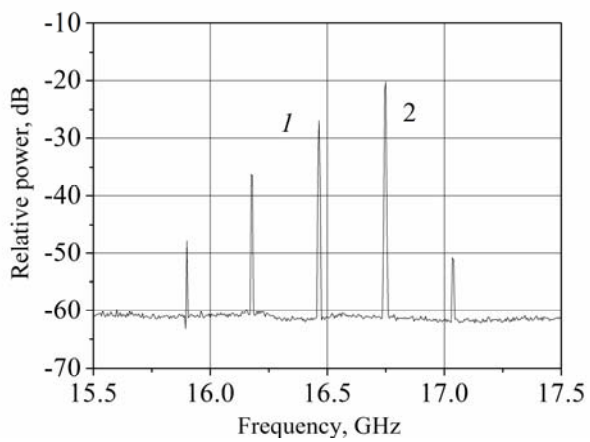



Fig. 8. The width of external synchronization band for single active antenna (*1*) as well as for linear arrays consisting of two (*2*) and three (*3*) mutually synchronized antenna-oscillators versus the power flow density of the external signal.

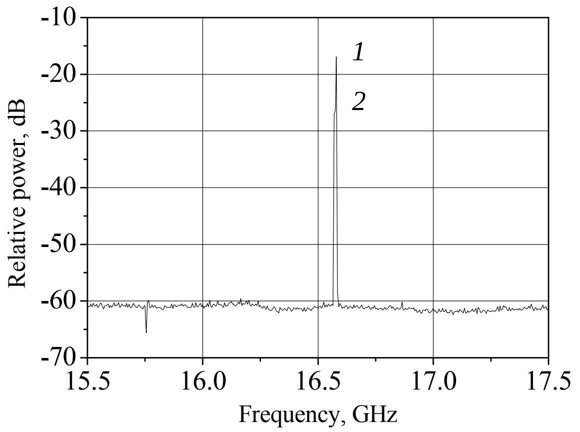
The resulting radiation spectrum contains generation *1* and synchrosignal *2* frequencies and combination components between them.




(*a*)




(*b*)




(*c*)

Fig. 9. The radiation spectrum of array consisting of tree active antennas synchronized by external signal: (*1*) radiated signal frequency; (*2*) external signal frequency.

In the case of external signal frequency located inside the synchronization band (~150 MHz), the full synchronization occurs and the generation of the antenna-oscillator array is observed at the frequency of the synchronization signal as illustrated in Fig. 9*c*.

Fig. 10 shows radiation patterns of array consisting of four antenna-oscillators for several operation modes. The measured output power levels of this antenna-oscillator array are presented in the Table 1. Radiation patterns were measured in the longitudinal plane of the array normal to the antenna surface. In the transversal plane, the width of the radiation patterns was the same as for the single antenna-oscillator.

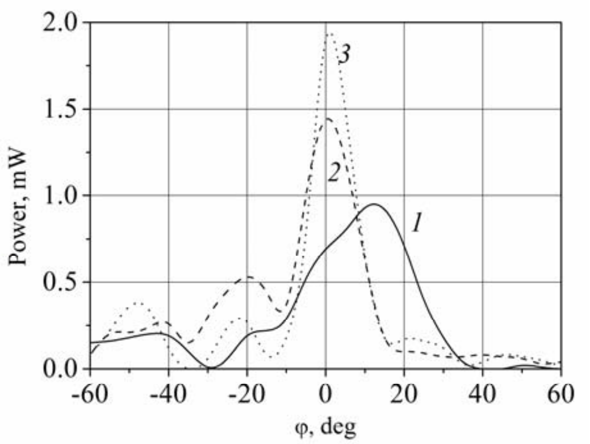



Fig. 10. Radiation patterns of the linear array consisting of four antenna-oscillators for the case when active antennas are: (*1*) not synchronized; (*2*) mutually synchronized; (*3*) synchronized with external irradiation.

The width of radiation pattern φ was measured at the level –3 dB. The full radiated power $P_0$ was defined as:

$$P_0 = P_{meas}(4\pi R / \lambda_0)^2 / (G_{ant} G_{feed}),$$

where $P_{meas}$ is a power measured in the maximum of radiation pattern; $G_{ant}$, $G_{feed}$ are directional factors of active antenna and receiving feed antenna, respectively; $R$ denotes the distance between active and receiving antennas.

Table 1. Radiation parameters of the active antenna array in various synchronization modes.

| Radiation parameters | φ, deg | $P_{meas}$, mW | $P_0$, mW |
|---|---|---|---|
| Single active antenna | 65 | 0.17 | 7 |
| Active antenna array without synchronization | 30 | 0.93 | 14.9 |
| Active antenna array with mutual synchronization | 17 | 1.44 | 13.7 |
| Active phase antenna array with external synchronization | 13 | 1.9 | 14 |

The data indicated in Fig. 10 as well as in the table show that partial narrowing of the radiation patterns can be observed in the absence of synchronization signal due to the mutual influence of antenna-oscillators. In this case, the radiation patterns remain wide and non-symmetrical. The influence of the external synchronizing signal results in additional radiation patterns narrowing and increasing of the output power.

## Synchronization of the linear array in the resonator

The external synchronization allows considerably increasing the locking frequency band of active antenna and enhancing the efficiency of power combining but it requires including an external source of synchrosignal that makes the scheme more complicated. The possibility of increasing the interaction between active antennas by applying the quasi-optical resonator was also investigated to increase the mutual synchronization band. If the polycor dielectric reflector is to be located near antenna array parallel to its plane as in [3], the mutual synchronization frequency band of active antennas can reach the value of 140 MHz.

Radiation patterns of the array consisting of three active antennas are shown in Fig. 11 for the case when the differences in their own frequencies constitute ~100 MHz. The graph *1* represents the radiation pattern of array in which the active antennas are not mutually synchronized. The curve *3* depicts the radiation pattern of array consisted of the active antennas which are effectively synchronized in presence of the reflector. The shape of radiation pattern in the case of the reflector absence under condition of mutual synchronization is shown by curve *2*.

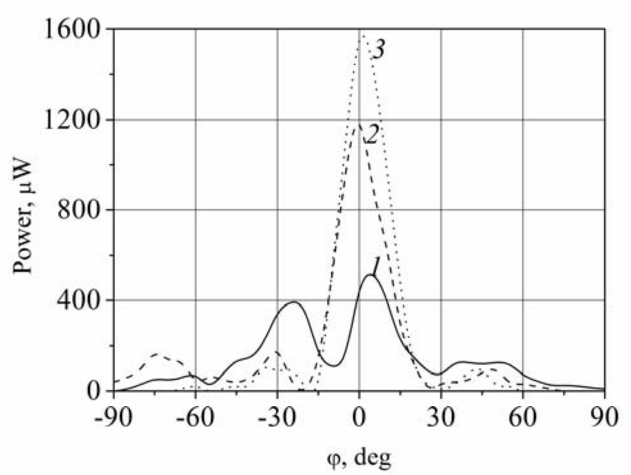



Fig. 11. Radiation patterns of linear array consisting of tree active antennas: (*1*) without external synchronization; (*2*) with external synchronization; (*3*) with mutual synchronization in presence of the reflector.

The comparison of curves depicted in Fig. 10 and Fig. 11 proves that the influence of standing wave formed in quasi-optical resonator on characteristics of the active antenna array is effective as like as the irradiation by the external synchronizing wave.

## Conclusion

Log-periodic planar antenna integrated with field-effect transistor is a compact and effective source of electromagnetic wave radiation in the wide frequency range. Such antenna-coupled oscillators can be used as active elements of antenna arrays. Mutual and external synchronization of oscillators in the linear array are used for increasing the generation efficiency and space power combining accuracy.

Active antennas performed as a linear array placed on the common dielectric substrate can be synchronized due to interactions of surface waves in the substrate if the discrepancy of their own frequencies is less than 50 MHz or by the external irradiation when this discrepancy can reach 150 MHz. The influence of the external synchronizing signal results in additional radiation patterns narrowing and increasing of the output power.

Active antennas in the linear array inserted to the quasi-optical resonator can be mutually synchronized if the discrepancy of their own oscillation frequencies do not exceed 150 MHz and effective power combining is possible. It is proved that the influence of standing wave formed in quasi-optical resonator on characteristics of the active antenna array is effective as like as the irradiation by the external synchronizing wave.

Active integrated antennas and arrays designed and investigated above are prospective for applications as portable microwave and millimeter wave power sources in various telecommunication systems.

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