ACTIVE INTEGRATED ANTENNAS WITH SINGLE AND PUSH-PULL TRANSISTOR OSCILLATORS

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Abstract: *The paper presents the R&D in the field of active integrated antennas at the University of Zagreb. Several prototypes with single transistor oscillator and two-transistor push-pull oscillator are designed, manufactured and subjected to experimental verification of their characteristics. Rectangular, square and circular microstrip patches are used. The possibility of obtaining linear and circular polarizations is investigated. Integration of several active antennas in mutually injection locked antenna arrays is studied. Power combining and beam scanning capabilities are demonstrated.*

Introduction. Active integrated antennas and arrays find their applications in communications and radar systems. Besides fabrication simplicity and low manufacturing costs, the main advantages of active integrated antenna arrays are the possibility of free space power combining [1, 2] and beam scanning without phase shifters [3]. By combining power from multiple sources in free space the losses in combining circuits are avoided. All array elements have to be mutually injection locked. Injection locking is achieved through mutual coupling between the array elements. The coupling can be weak (mainly radiative [1]) or strong (e.g. by using coupling lines [4] or integrating spatial oscillators in grids [5]).

The active arrays described in this paper use weak, radiative coupling. The coupling strength and phase are determined in terms of the inter-element distance. To facilitate the adjustment of the operating frequencies of the array elements it is most convenient that all elements operate at the same frequency. Usually, it is desirable to obtain maximum power combining in the direction perpendicular to the plane of the array, i.e. at broadside. With all elements operating at the same frequency, this is obtained by adjusting the inter-element distance for the coupling coefficient phase of 0°. Also, the analysis and stability considerations in [3] showed that the coupling coefficient phase around 0° gives the best results for weakly coupled spatial power combining arrays.

When the active antennas are going to be integrated in an array it is desirable that their dimensions remain as small as possible. By embedding the active circuitry inside an opening in the patch, the antenna dimensions are not increased. In fact the rectangular opening inside the patch lowers its resonant frequency i.e. to operate at the same frequency as the unmodified patch the patch with an opening has to be smaller. The opening dimensions should be large enough for embedding the oscillator circuit and, where used, the impedance matching network, but should also be as small as possible to reduce the disturbance of the current distribution on the patch and allow the excitation of the desired operating mode. Very important issue is the geometrical symmetry of the active antennas. By maintaining the symmetry good radiation properties can be obtained and the cross-polarization levels can be reduced.

To analyze and optimize the patch radiators with openings and to optimize the inter-element distance in arrays the IE3D electromagnetic simulator from Zeland Software, Inc. was used. All antennas and arrays have been manufactured on the same substrate having the height of 1.576 mm, relative dielectric constant of 2.55 and the loss tangent of 0.0019.

The presented active integrated antennas and arrays are result of the research performed at the Department of Radiocommunications and Microwave Engineering at the Faculty of Electrical Engineering and Computing in Zagreb. Earlier results in the same field, concerning active integrated antennas with one-port active devices can be found in [6].

Active antenna with transistor oscillator and line transformer. The patch antenna with a line impedance transformer and a transistor oscillator was described in [7]. The rectangular patch was designed for operation in TM_{01} mode at the frequency of 2.3 GHz. The patch dimensions were 42.3 mm × 34.7 mm. The oscillator circuit and the impedance matching network were placed inside a 10 mm × 25 mm rectangular opening, which has been made symmetrically in the patch. The patch is excited at its line of symmetry on one of the opening edges. The relatively high impedance at the center of the opening edge has to be transformed to lower impedance that satisfies the conditions for starting of the oscillations [6]. Suitable impedance transformation has been achieved with 5 mm × 13.7 mm microstrip line.

Hewlett-Packard AT-41485 NPN bipolar transistor in common collector configuration was used as active device for the oscillator. An inductive short-circuited stub for destabilization was connected to the transistor base terminal, while the emitter terminal was the output and it was connected to the line impedance transformer. The dc bias was realized by negative dc voltage connected through a high impedance microstrip line to the center of the patch non-radiating edge. A resistor from the collector to the base provided the base dc biasing. The active patch layout is shown in Fig. 1.

By changing the dc bias from 2 to 9 V the frequency changed from 2.2473 GHz to 2.2888 GHz. The change of the oscillating frequency with the bias voltage was very linear. Maximal *EIRP* of 19.4 dBm was measured at 9 V dc bias. Measured radiation patterns were not affected by the modification inside the patch and by the active circuitry. Cross-polarization levels were bellow –23 dB in E-plane and bellow – 17 dB in H-plane.

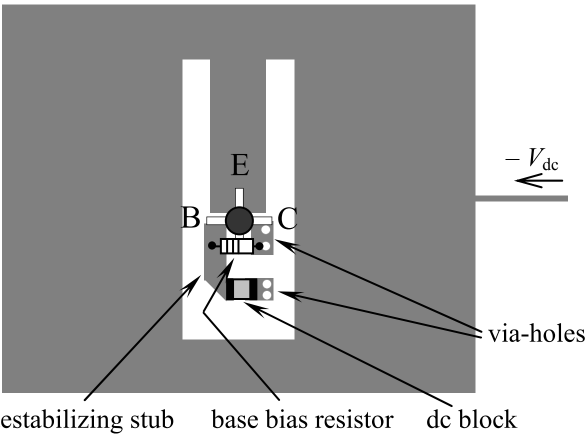

Fig. 1. Active antenna with transistor oscillator and line transformer

Two of these active antennas were integrated in arrays coupled in E- and H-planes. For the E-plane array the desired coupling coefficient phase of 0° at the operating frequency of 2.3 GHz was achieved for the inter-element distance of 0.72 λ_0, while for the H-plane array the inter-element distance was 0.85 λ_0. Here λ_0 denotes the free space wavelength. Power combining efficiency of 105 % and 97 % were obtained for the E- and H-plane arrays, respectively. The combining efficiency larger than 100 % in the case of E-plane array can be explained by better impedance matching between the oscillator and the patch antenna obtained in the array due to the interaction between the array elements.

By adjusting the bias voltages of the oscillating antennas in the array within the mutual injection locking range, the phase of the signal, radiated by the antenna, is changed. In this way electronic beam scanning without phase shifters is obtained. Beam scanning capabilities for both power combining arrays were examined. Symmetrical beam scanning around broadside was obtained in both cases by changing the bias voltage of one of the array elements. The E-plane array showed a beam scanning of ±17° and the H-plane array a beam scanning of ±11° around broadside. Co-polarization and cross-polarization radiation patterns have been measured for broadside radiation and for both maximal obtainable scanned positions of the main beam. The cross-polarization levels for broadside radiation as well as for both scanned beam positions were for all angles bellow –20 dB for the E-plane array and bellow –19 dB for the H-plane array. The measured spectra of the signals radiated by both arrays were clean and stable.

Push-pull oscillator. In order to increase the power radiated by a single active antenna, a push-pull oscillator has been developed. The push-pull oscillator is shown in Fig. 2. Two Hewlett-Packard AT-41485 NPN bipolar transistors in common collector configuration were used as active devices for the push-pull oscillator. The common collector configuration was applied because it gives significant negative resistance in the frequency band of interest and, for the considered case, the transistor dc biasing is much simpler in comparison to the common base configuration. The transistor emitters were the oscillator outputs and they were connected to the patch excitation points on the opening edges. The transistor bases were connected together with a microstrip line. This line has double role in the oscillator. First, it provides suitable loading at the transistor input for obtaining negative resistance at its output. Also, it assures that the two transistors operate with 180° phase shift. By satisfying both requirements with a single line, the substrate area occupied by the oscillator is reduced. Therefore a smaller opening in the patch was required. As any two-element system, the oscillator with two transistors can operate in odd and even modes. The resistors R_S connected from the middle of the line to the ground plane suppress the even operating modes of the oscillator [8]. A resistor R_B from the collector to the base provided the dc biasing of the base. Only the resistor R_E and the inductors L (Fig. 2) are placed outside the patch.

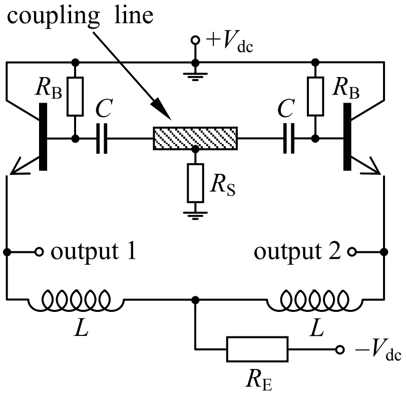

Fig. 2. Push-pull oscillator

Rectangular patch antenna with push-pull oscillator. The oscillating antenna with push-pull oscillator (Fig. 3) was introduced by the authors in [9]. The push-pull oscillator was embedded in a rectangular opening made inside the rectangular patch. The rectangular patch dimensions were 47.2 mm × 38.68 mm and the rectangular opening dimensions were 14 mm × 12.5 mm. The opening was placed symmetrically inside the patch. The resonant frequency of the TM_{01} mode was 2.1 GHz.

The topology of the push-pull oscillator, described in the former section, was adapted to fit in the opening in the patch. The two transistors were placed along the patch resonant dimension on the line of symmetry of the patch. The dc bias was realized by negative dc voltage connected by a high impedance microstrip line to the center of the patch non-radiating edge. The active antenna layout is shown in Fig. 3.

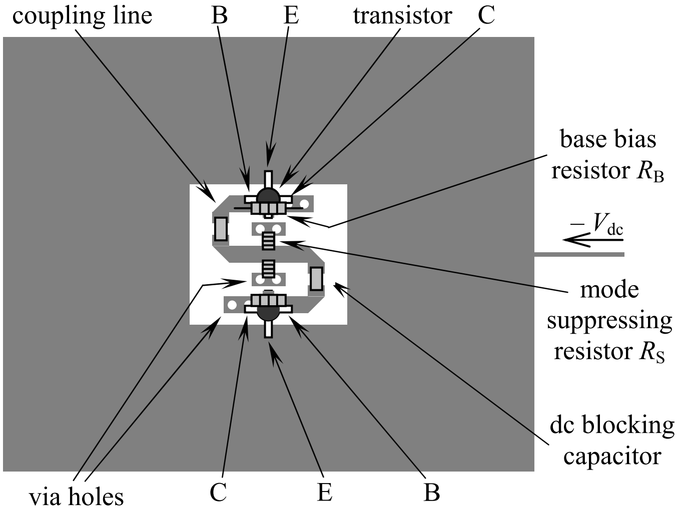

Fig. 3. Active rectangular patch with push-pull oscillator

By changing the dc bias voltage in the range 1 ÷ 11 V, a linear frequency tuning from 2.0908 to 2.1202 GHz was obtained. At 11 V bias maximal EIRP of 24.4 dBm was measured. The operation was stable and the measured spectra were clean. Measured radiation patterns showed no degradation in comparison to a non-modified passive patch. Measured cross-polarization levels were bellow –21 dB in E-plane and bellow –19 dB in H-plane.

By integrating this oscillating antenna in an array a two-level power combiner is obtained. The first level of power combining occurs at circuit level by using two transistors in the oscillator. The second level is free space power combining.

Considering that each array element has two ports, the discussion on the coupling coefficients is more complicated than in the previously described case. Thorough analysis can be found in [10]. Still holds the fact that if all active antennas in the array operate at the same frequency, the inter-element distance can be optimized for optimal mutual injection locking conditions.

Table 1. Power combining arrays of rectangular patch antennas with push-pull oscillator

No. elements	Coupling plane	Array element distance	EIRP [dBm]	Combining efficiency	Beam scanning range	Maximal cross-pol levels [dB]
2	H	0.82 λ_0	27.9	95 %	±12°	–20
2	E	0.60 λ_0	28.2	96 %	±11°	–18
3	E	0.69 λ_0	31.5	95 %	±8°	–17
4	E	0.69 λ_0	33.6	83 %	±11°	–22

A two-element array coupled in H-plane and two-, three- and four-element arrays coupled in E-plane have been designed, manufactured and experimentally investigated. The inter-element distance for the two-element array in H-plane was 0.82 λ_0. The inter-element distance for the two-element array in E-plane was 0.60 λ_0, while for the three- and four-element arrays the distance was 0.69 λ_0.

The performances of these power combining arrays have been experimentally verified. High EIRP and very good power combining efficiency have been measured. Beam scanning capabilities for all four arrays were examined. All arrays showed symmetrical beam scanning around broadside. The results are shown in Table 1. The co-polarization and cross-polarization radiation patterns were measured for broadside radiation and both maximal scanned positions of the main beam. The worst case cross-polarization levels are also given in Table 1.

Circular patch antenna with push-pull oscillator. The described push-pull oscillator has been integrated with a circular patch [11]. After optimization, the circular patch radius was 23.3 mm and the resonant frequency of the TM$_{11}$ mode was 2.1 GHz. The rectangular opening dimensions were 19.5 mm × 11 mm. It has been placed symmetrically inside the patch to allow the embedding of a push-pull oscillator (Fig. 4).

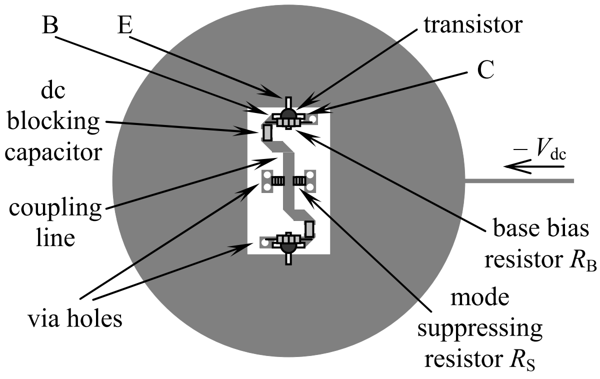

Fig. 4. Active circular patch with push-pull oscillator

A maximal *EIRP* of 25.3 dBm has been obtained at 10 V dc bias, which is better than the result obtained with the rectangular patch. This can be explained by better impedance matching between the patch radiator and the oscillator. By changing the dc bias in the range 1 ÷ 10 V, the frequency of the radiated signal changed from 2.0757 GHz to 2.1053 GHz. The change of the operating frequency with bias voltage was very linear. The active patch operating frequency and the calculated patch resonant frequency agree very well. Throughout the tuning range this active antenna showed good spectral purity. The content of the second harmonic in the radiated signal was 3 ÷ 4 dB lower in comparison to the rectangular active patch. This could be expected since circular patches have higher quality factor in comparison to the rectangular ones. The measured cross-polarization levels were below –21 dB in E-plane and bellow –20 dB in H-plane for all angles, which is also a slightly better result than in the case with the rectangular patch.

Circularly polarized active antenna. A square microstrip patch excited in two points with signals having equal amplitudes and 90º mutual phase shift radiates circularly polarized signal. The patch was excited with the previously described push-pull oscillator which is again placed in a square opening inside the patch [12]. The signals at the oscillator outputs have 180º mutual phase shift, while the patch has to be excited with two signals of equal amplitudes and 90º phase shift. Therefore, an additional phase shift of 90º was introduced in one of the oscillator outputs by placing a quarter-wavelength long microstrip line. The patch was designed for operation at 2.1 GHz. The final patch dimensions were 35 mm × 35 mm and the opening dimensions were 18 mm × 18 mm. The opening center was displaced 3 mm left and 3 mm down with respect to the center of the patch. The microstrip line for obtaining the additional 90º phase shift was 24.5 mm long and 0.75 mm wide. The antenna is shown in Fig. 5.

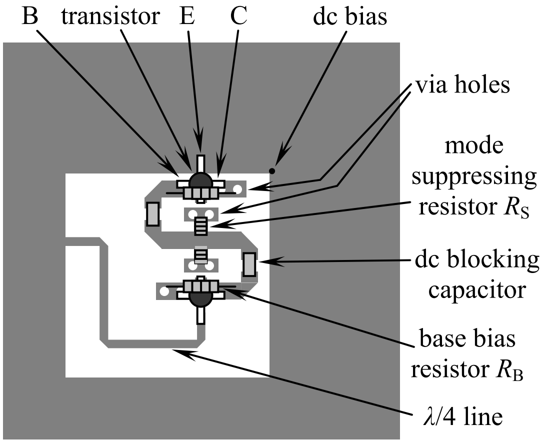

Fig. 5. Active circularly polarized antenna

At 7 V bias a maximal *EIRP* of 12.2 dBm was measured. At the same bias voltage the operating frequency is 2.0811 GHz. Due to the inherent asymmetry the antenna always radiates left-handed circularly polarized wave (LHCP). At 7 V bias the measured axial ratio at broadside was 2. This is due to the difference in amplitudes at the oscillator outputs resulting from different loading of the two oscillator ports (the quarter-wavelength long microstrip line at one oscillator port acts as an impedance transformer). The measured axial ratio at 11 V is 1.3, but at this voltage the *EIRP* is lower.

Conclusion. Several active integrated antennas and active arrays have been presented. All active antennas showed linear frequency tuning and high *EIRP*. The arrays had very good power combining efficiencies and for all beam scanning capabilities were demonstrated. The common approach for all presented active antennas was the integration of the active circuitry inside an opening in the patch resulting in small and compact active antenna modules. Same approach demonstrated its applicability and advantages when one-port active elements were used [6]. Symmetrical oscillator topology and, when possible, symmetrical layout of the whole active antenna gave good radiation properties. The main advantages are that radiation patterns were not perturbed by the modifications inside the antenna and by the active circuitry and that the cross-polarization levels were low.

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