A Capacitively-Coupled Series-Fed Patch Leaky-Wave Antenna and Optimization Concepts for Efficient Broadside Radiation

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***Abstract*—This paper presents a novel series-fed patch leaky-wave antenna (LWA) and furthermore demonstrates optimization strategies for achieving efficient broadside radiation. The proposed LWA is based on the concept of a proximity coupled microstrip patch antenna. Here, two feeding lines from both sides couple capacitively to the microstrip patch edges to form a unit cell element of the LWA. This capacitively-coupled series-fed patch (CSFP) LWA offers several advantages over a conventional series-fed patch LWA, as it provides, a broadband 50 Ohm input impedance, electrically independent tuning parameters and most importantly the total elimination of the open-stopband problem (standing-wave phenomena) at broadside. Finally, CSFP prototypes for 24 GHz are presented with input impedance, scattering parameter and gain measurement results for validation of the proposed designs.**

***Index Terms*—Leaky-wave antenna, broadside radiation, series-fed patch (SFP), proximity coupled patch.**

I. Introduction

Periodic Leaky-wave antennas are well investigated in the literature [1],[2]. They belong to a group of traveling wave antennas, where the power leaks out of the structure at periodic discontinuities and radiates into free space, while a traveling wave is guided along the antenna. A one-dimensional periodic LWA is composed of a certain number of identical cells (unit cells) along the antenna axis, where the end of the antenna is terminated with a match load. In these types of antennas the radiation beam is controlled by frequency and might be steered through the broadside direction.
A general problem in periodic LWAs arises when the antenna radiates broadside, which corresponds to a zero or 360° degree phase shift across each unit cell depending on the space harmonics ($n = 0$ or $n = -1$) that radiates. This issue is referred to as the open-stopband problem or the standing-wave phenomena [2]. A composite right/left-handed LWA and a stub-loaded LWA optimized for broadside radiation have been reported in [3] and [4], respectively to overcome these issues. The broadside radiation characteristics of a conventional series-fed patch (SFP) LWA has been examined in [5] as a case study example, where a rigorous two port modeling approach for one-dimensional transversally symmetrical[1] LWAs has been established. In this two port modeling approach effective series and shunt resonators have been defined with resonance frequencies f_{se} and f_{sh}, respectively. A necessary condition for closing the band gap and radiating trough broadside is the frequency balancing condition with $f_{se} = f_{sh} = f_0$ (known from metamaterial transmission line theory [6]), where f_0 is the broadside frequency.
In this paper, we present a novel periodic LWA, based on the SFP design in combination with the concept of capacitively-coupled patches. This concept has an additional degree of freedom over the conventional SFP LWA, since the patch is floating above the feeding line. Together this forms the capacitively-coupled series-fed patch (CSFP) LWA. This new design is optimized with two different approaches to overcome the aforementioned broadside radiation problem by minimizing the impedance variation around the broadside frequency, where the first optimization approach uses a quarter wave transformer for unit cell matching, which is similar to the method proposed in [3]. The second approach simply shifts the patch element along the longitudinal axis (y-axis in Fig. 1(a)) for achieving unit cell matching. Furthermore, the proposed CSFP LWA can be designed to exhibit a constant 50 Ω input impedance by tuning the ratio of the patch width and the feeding line width, while the conventional SFP suffers from a high input impedance [5]. Another advantage lies in good polarization purity, since the CSFP Antenna is totally symmetrical with respect to the longitudinal axis.

II. Capacitively-coupled series-fed patch Leaky-wave antenna (CSFP LWA) Design

The antenna Layout is shown in Fig. 1(a). It consists of a multi-layer PCB. Fig. 1(b) shows the yz-cut of the stack, where the floating patch and the feeding lines are illustrated and in Fig. 1(c) the xz-cut is given, where the different widths of the patch and the feeding line are shown. The stack has two Rogers RO4350 cores with height $h_1 = 250\ \mu m$, $h_3 = 168\ \mu m$ and $\varepsilon_r = 3.66$ and one prepreq Rogers RO4450 with hight $h_2 = 100\ \mu m$ and $\varepsilon_r = 3.77$. The feeding line is stacked on the first core under the patch, where the coupling occurs in the overlap between the line and the patch. The length of the patch is approximately half a guided wavelength $l_p \approx \lambda_g/2$ and the feeding line $l_l \approx \lambda_g/4$, where the total period p of the unit cell is approximately one guided wavelength $p \approx \lambda_g$.
The FDTD simulator EMPIRE^{TM} XCcel has been used to optimize the unit cell of the CSFP antenna in Fig. 1(a). First, we optimize the unit cell to obtain the frequency balancing with $f_0 = f_{se} = f_{sh}$. For this optimization only two geometrical

[1]Transversally symmetrical refers to the symmetry with the x-axis as symmetry axis, shown in Fig. 1(a).

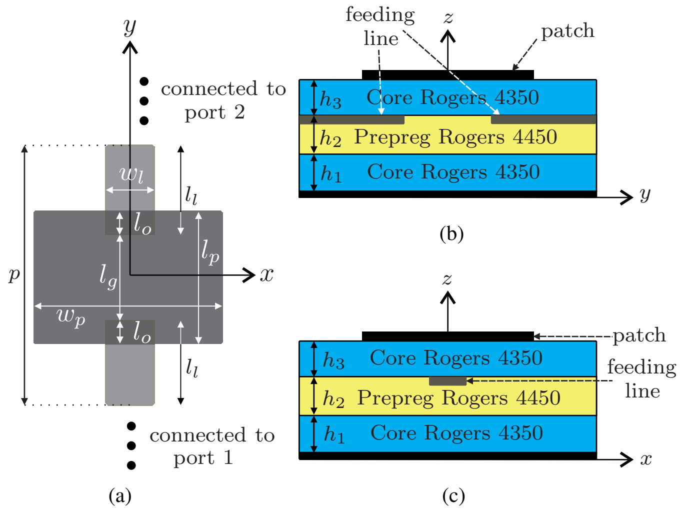


Fig. 1. The CSFP antenna unit cell. (a) Top view with the geometrical parameters. (b) Side view of the *yz*-plane, the overlap between the feeding line and the patch is shown. (c) Side view of the *xz*-plane.

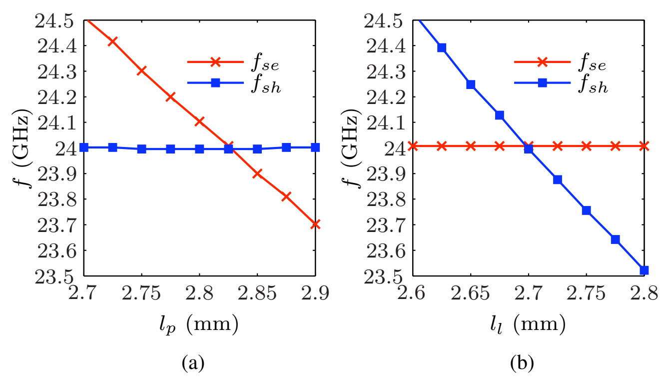


Fig. 2. The dependency of the resonance frequencies f_{se} and f_{sh}. (a) The series frequency can be tuned individually by varying the patch length l_p and (b) the shunt frequency can be tuned individually by varying the line length l_l.

parameters are needed the patch length l_p and the line length l_l. Fig. 2 shows the resonance frequencies f_{se} and f_{sh} in dependence of l_p and l_l. Here, one geometrical parameter is kept constant, while the other is varied. It can be clearly seen that the series f_{se} and shunt f_{sh} frequency can be separately tuned by a single parameter, which in turn, makes the practical frequency tuning of this structure very simple. After obtaining the frequency balancing, the following two approaches can be used to optimize the antenna for a flat input impedance around the broadside frequency.

A. Quarter-Wave Transformer Design

In Fig. 3(a) a top view of the unit cell with the optimization parameter w_t is given. This approach uses the $\lambda_g/4$ feeding line to introduce transversal asymmetry to the structure and we further refer to this shortly as transformer design.

B. Patch Offset Design

The top view of the layout is shown in Fig. 3(b). This design exploits the additional degree of freedom of the CSFP

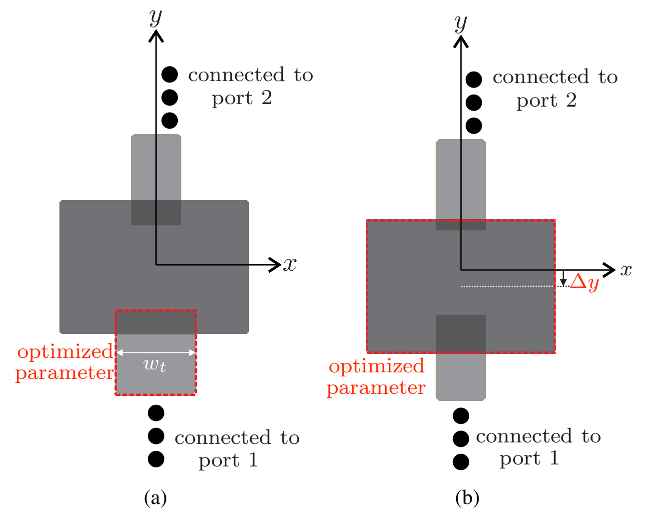


Fig. 3. The layout configuration of two asymmetrical approaches of the CSFP antenna for a flat input impedance with frequency.(a) Illustration of the transformer design approach, where the feeding line width w_t is tuned and (b) the patch offset design, where the patch is shifted Δy along the *y*-axis (longitudinal axis).

LWA over the conventional SFP LWA. The floating patch is shifted along the longitudinal axis. The shift will change the overlapping length l_o and therefore the capacitance. In other words, the capacitance will increase at one side and decrease at the opposite side.

After using one of these approaches the frequencies f_{se} and f_{sh} may suffer from a slight shift due to the change of geometrical parameters. They have to be re-optimized for the frequency balanced case.

III. Discussion of Simulated and Experimental Results

In Tab. I the geometrical dimensions are listed for both designs of CSFP antennas at 24 GHz for optimum flat input impedance with frequency. Starting with the transformer design, the feeding line width from port 1 is $w_t = 1.45$ mm and from port 2 is kept constant $w_l = 1.3$ mm. For the patch offset design a patch offset $\Delta y = 0.4$ mm is required to obtain a frequency independent input impedance. The fabricated prototypes are given in Fig. 4, the transition is shown in the dashed box. Blind vias have been used to feed the buried feeding line of the first unit cell from the top layer. First, we measure the network parameters by using a TRL calibration technique, which allows to measure the exact input impedance without the effect of the connectors and the transitions. Next, we compare the input impedance obtained from simulation and measurement for both transformer and patch offset designs in Fig. 5(a) and Fig. 5(b), respectively. A broadband input impedance can be seen from port 1 for both approaches, while the input impedance for port 2 degrades. In general, we have a very good agreement between the simulation and measurement.

Next, we will discuss only the measurement results. With the constant input impedance of $Z_{in,1}$=50 Ω seen from port 1, a broadband matching is expected. Fig. 6 shows the measured S-parameters for both designs, it can be seen that the reflection

TABLE I
GEOMETRICAL DIMENSIONS IN MM OF THE CSFP ANTENNA

	w_l	w_p	l_p	$l_l/2$	l_g	l_o	Δy	w_t	p
transformer Fig. 3(a)	1.3	4.5	2.8	2.70	1.50	0.65	-	1.45	6.85
patch offset Fig. 3(b)	1.3	4.5	2.8	2.75	1.35	1.10	0.40	-	6.85

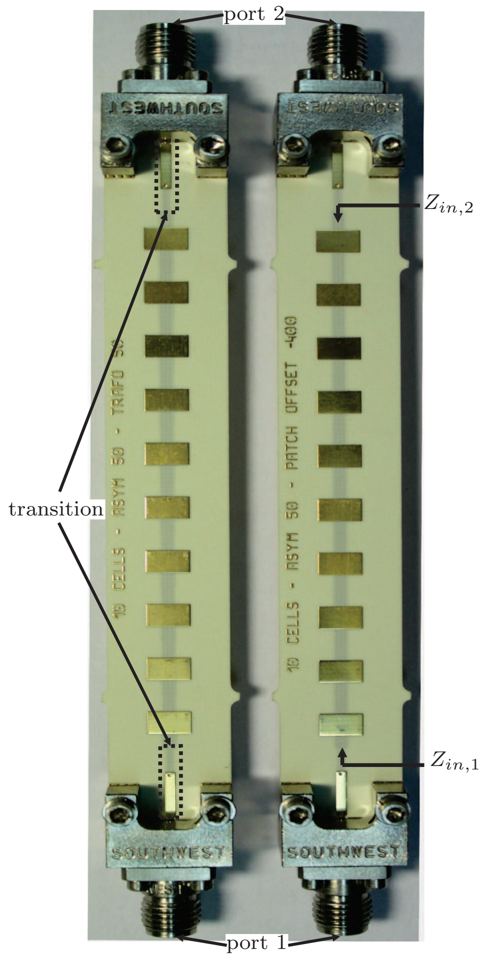
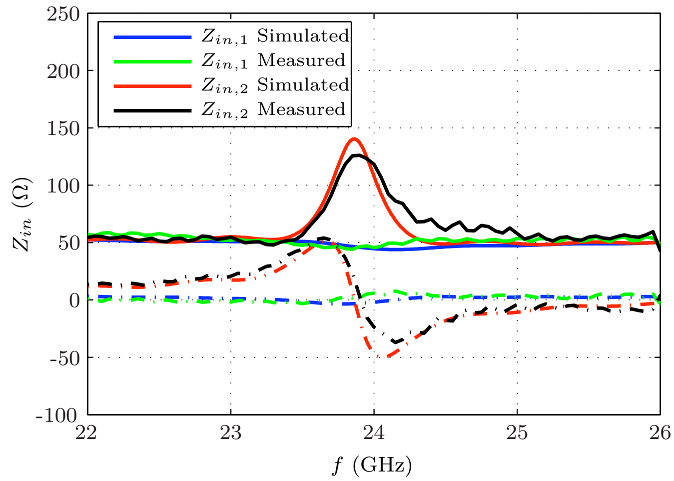
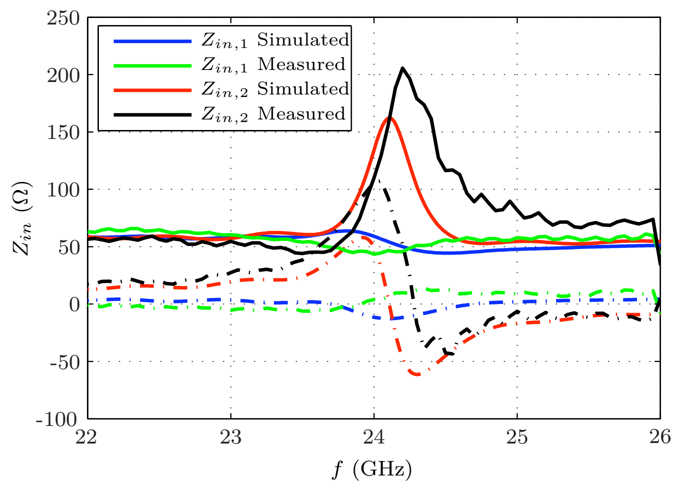


Fig. 4. The fabricated prototypes with connectors (left: transformer design and right: patch offset design). The transition is depicted in the dashed box to feed the antenna from the top to the middle layer.



(a)



(b)

Fig. 5. Comparison of the input impedances (real part: solid lines and imaginary part: dashed lines) of the 10 unit cells CSFP antennas showing simulation and measurement results. (a) Transformer design and (b) Patch offset design.

coefficient $|S_{11}|$ is lower than -15 dB for both transformer and patch offset designs. Here, it has to be considered that the TRL calibration in this microstrip environment may be only accurate down to a matching level of -15 dB. As for port 2 we see a large mismatch $|S_{22}| > -10$ dB around the 24 GHz broadside frequency.

Lastly, the antenna gain has been measured by using farfield measurement techniques, where the gain of the antenna is obtained after calibrating the measurement system using a standard gain horn (SGH) antenna. In Fig. 7(a) the measured gain of both, transformer and patch offset designs is plotted for three frequencies 23 GHz, 24 GHz and 25 GHz, where the main beam is scanning through broadside. A constant gain is observed due to the optimized approaches, when the antenna is exited from port 1. The patch offset design has the maximum gain of 13.4 dBi. The measured gain of port 2 is given in Fig. 7(b), the gain is constant for frequencies of 23 GHz and 25 GHz for both designs, but it degrades at 24 GHz. The transformer design has a gain of 9.7 dB and the patch offset design has 7 dB, where this difference is caused by the larger mismatch of the patch offset design at broadside.

IV. CONCLUSION

A novel capacitively-coupled series-fed patch CSFP LWA with two optimization concepts for efficient broadside radiation has been presented. Two optimized LWAs have been fabricated and measured. Both antennas exhibit a broadband matching and a constant gain, while the main beam is scanning

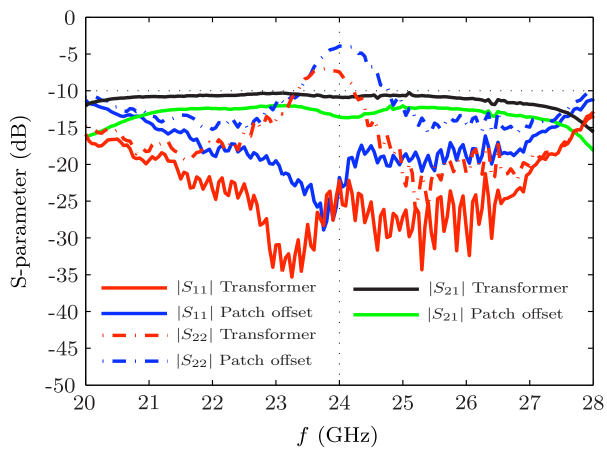
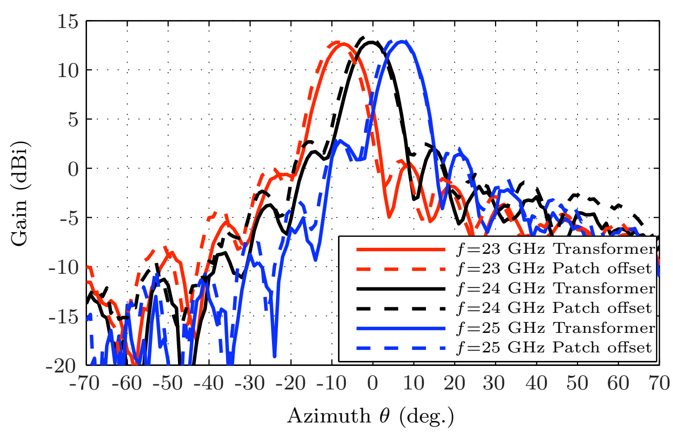
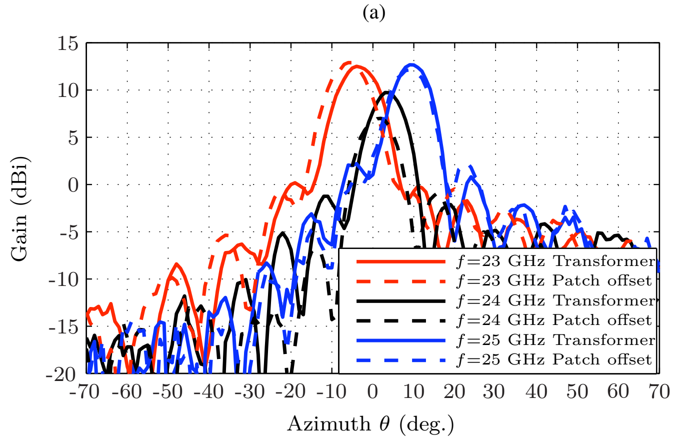


Fig. 6. Measured S-parameters of the 10 cells CSFP antennas, the transformer and patch offset designs. An excellent matching is observed fro port 1 and an antenna performance degradation for port2.



(a)



(b)

Fig. 7. Measured gain of the 10 cells CSFP antenna of the transformer and patch offset designs. The antennas are measured from both ports. (a) Excitation from port 1, where a constant gain is achieved, while the main beam is scanning with frequency. (b) Excitation from port 2, where a performance degradation for the gain at the 24 GHz broadside frequency is observed.

through broadside. In this work, it has been demonstrated that using asymmetry in LWA unit cells, it is possible to optimize a periodic LWA for a particular excitation side (port), while the other side is severely degraded. Since many LWAs are operated from a single side, this trade-off can be easily made.

Acknowledgment

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