Filter-Bank-Enabled Leaky-Wave Antenna Array Technique for Full-Band-Locked Radar System in Stitched Frequency-Space Domain

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Abstract — Inspired from the filter-bank (FB) concept that is normally used for multirate signal processing, an FB-enabled array technique of leaky-wave antennas (LWAs) is proposed and studied for creating full-band-locked frequency-scanning radar systems in a stitched frequency-space domain. This is mainly for addressing the coupling dilemma between the range and angle resolutions that is historically and naturally inherited from a conventional frequency-scanning radar. FB-related conditions for the required “frequency-space stitching” (or full-band beam-target illumination) in radar operation are described and translated into the design specifications of an array of LWAs, such as engineered beam-scanning functions, beam-crossovers, and phase alignments. For a direct proof of concept, a practical two-channel LWA array is modelled, fabricated, and measured. Simulated and measured results are in a reasonable agreement, which exhibit the highly desired “frequency-space stitching” behaviour. The proposed FB-enabled array solution may present a potential competitor against the prevailing phased array.

Keywords — antenna array, filter bank (FB), frequency-scanning radar, full-band-locked beam illumination, frequency-space domain, leaky-wave antenna (LWA), phased array, range-angle resolution, spatial stitching, spectral stitching.

I. INTRODUCTION

In the radar world, the frequency-scanning radar (FSR) is featured with a unique status since it can behave as a trade-off solution in terms of radar detection performances and system costs/complexities compared to mechanical and phased array radars [1][2]. This is because, for example, compared to a mechanical radar, the frequency-scanning counterpart is apparently much faster in scanning a space without inertial devices such as the required electric motors and rotors. Also, compared to a phased array system, its beam-scanning does not necessitate expensive and lossy phase shifters or time-delay devices together with extra phase-controlling circuits. These merits for an FSR are substantiated by its scanned beam being enabled with frequency (i.e., frequency-driven beam-scanning), which, interestingly, is also an inborn feature of leaky-wave antennas (LWAs) [3][4]. Given this, FSRs, or LWA-enabled radars as will be used synonymously in this paper, have been continuously being explored and developed by researchers [5]-[8].

Consider the fact that each coin has two sides. The frequency-scanned beam, unfortunately, brings FSRs a dilemma of coupling regarding the range and angle resolutions [2]. As a side note, this issue, in historic times, was in parallel with the contradiction problem between the range resolution and detection range in pulse radars which, however, has been successfully resolved by using modulated pulse waveform together with pulse compression techniques. Comparatively, the range-angle resolution coupling problem in FSRs, to the best of the author’s knowledge, still remains to be solved to date. One not-so-well-noticeable but intuitive observation in FSRs is that there is no possibility to achieve a beam illumination on a given target or spot over a full band of interest because of the frequency-scanning behavior. In other words, any given target or spot can only “see” a small portion of all the frequency components within an allocated full-band, depending on the LWA beamwidth and scanning rate, as will be described later. Perhaps this is the fundamental reason why the FSRs have historically been prevented from being popularized in numerous application scenarios that require high radar detection performances, and therefore these areas have been dominated for a long time by other radar techniques, especially by the phased array technique.

After carefully examining the frequency-space domain on which phased array (or mechanical) radars normally operate, as shown in Fig. 1(a), and then comparing it with the counterpart that belongs to FSRs (or LWA-enabled radars) as depicted on the left-hand side of Fig. 1(b), we come up with a...
scheme called “frequency-space stitching” as sketched on the right-hand side of Fig. 1 for FSRs, aiming to beam-illuminate any given target over a given full band of interest and to effectively decouple the intractable range-angle resolution problem while maintaining those merits brought by the frequency scanning. This idea is inspired from the Filter Bank (FB) concept that is normally used in the field of multirate signal processing [9], and is enabled by an array of engineered LWAs. The uniqueness and superiority of the proposed solution mainly lies in the fact that its relevant radars are purely shifter-less and can be wideband, and possess good design freedom in terms of the range and angle resolutions.

II. PROBLEM ANALYSIS AND PROPOSED SOLUTION

A. Problem Analysis of Frequency-Scanning Radar

In this paper, we use frequency-modulated continuous-wave (FMCW) radars for demonstration thanks to their simplicity and popularity as well as their natural compatibility with a frequency-scanned beam owned by LWAs. Although in practice, like in automotive radars [10], multiple Tx-Rx chains are normally deployed in an FMCW radar to provide good angle estimation/resolution capabilities [1], only a single Tx-Rx chain is presented here for illustration convenience, as depicted in Fig. 2(a) which describes a simplified system block diagram of a typical FMCW radar except for the fact the traditional wideband fixed-beam Rx antenna has been substituted by an LWA (i.e., LWA-enabled FMCW radar). It should be noted that in conventional multi-channel FMCW architecture, both the Tx and Rx antennas are wideband and fixed-beam antennas, and a narrow beam will be produced in the digital domain and how narrow the beam depends on the number of Rx channels (or virtual channels if the MIMO technique were used). The beamwidth of such a digital narrow beam is equal to the angle resolution of this conventional multi-channel FMCW radar. Also note that in such a system architecture all the signal spectrum contents transmitted by Tx antennas can be received by Rx antennas without serious magnitude and phase distortion, and therefore almost the whole spectrum bandwidth of the signal waveform (e.g., chirp signal) can be exploited for the range resolution [1]. Unfortunately, this is not the case if an LWA is used as the Rx antenna. Due to the frequency-driven beam-scanning naturally endowed with an LWA as exhibited in Fig. 2(b), a spatially dependent bandpass filtering behaviour will be spontaneously performed if an LWA is used for receiving an incoming wideband chirp waveform. In this situation, only partial frequency spectrum can be received and possessed for an LWA-enabled FMCW radar. Thus, a waste of the wideband signal spectrum and deterioration of the range resolution are inevitably encountered (this issue would worsen when a narrower 3-dB beamwidth or equivalently a better angle resolution is needed). The related frequency-time diagram of the transmitted and received chip signals is disclosed in Fig. 2(c), and notably, different passband spectrums will be captured towards different angle-of-targets (AoTs). The bandwidth of the received spectrum, $\mathcal{B}R$, is basically related to the range resolution $\Delta R$ while the received spectrum bandwidth $\mathcal{B}R$ will determine the range resolution $\Delta R$ (i.e., $\Delta R = c / 2\mathcal{B}R$, $c$ is the light speed). Consequently, there must be a coupled relationship between the range and angle resolution of the LWA-enabled FSR, which can be expressed as

$$\Delta R \cdot \Delta \theta = \frac{c}{2} \frac{\Delta \theta_{3\text{dB}}}{\mathcal{B}R}$$  \hspace{1cm} (1)$$

B. Filter-Bank (FB)-Enabled LWA Array Technique

Consider that LWAs behave as a kind of spatially dependent band-pass filters and a single Rx LWA can only output a part of the whole spectrum of the incoming wideband signal waveform. Given this, for a certain AoT, if two or more Rx LWA channels with elegantly interleaved passband frequency responses could be used simultaneously and their individual received spectrums could be coherently superposed in the backend module, a synthesized spectrum bandwidth wider than a single LWA could capture may be formed for signal processing. Specifically, all of these LWA channels would corporately contribute to the range resolution, while each of them may be used for the angle resolution similar to [5]-[8]. In this regard, the range resolution could be significantly improved depending on the channel numbers while the angle resolution would remain the same as it would be with a single LWA channel. The two resolution-metrics are thus decoupled. For such a multiple-channel LWA array scheme, its frequency-space domain coverage would exhibit a “frequency-space stitching” phenomenon as illustrated on the right-hand side of Fig. 1(b). The proposed design scheme originates from the FB concept [9] as illustrated in Fig. 3(a), where its typical sub-band decomposition-summation process and the transfer function of each band-pass filter are presented. Here, a bank of frequency-interleaved band-pass filters are practically realized by a well-arranged array of LWAs, as simply illustrated in Fig. 3(b), while the relevant frequency-time diagram of the transmitted and received signals is conceptually plotted in Fig. 3(c). To obtain a gapless, stitched,
and bandwidth-enhanced spectrum toward a given AoT for the related radar, the transfer function of each “band-pass filter” (i.e., LWA channel) should be deliberately organized to ensure that the summed transfer function of the FB would present a widened and relatively flat frequency response. This requirement can be translated to several design specifications for the array of LWAs in terms of BSFs, beam-crossovers, and phase alignments. Because of the page limitation, detailed analyses are not possible to be given here. Instead, we choose to directly deliver several critical remarks about the design assumptions and specifications of the FB-enabled LWA array:

1. Each LWA in the array are assumed to possess a linear or quasi-linear BSF, and a constant 3-dB beamwidth and stable gain with frequency are also assumed. Each LWA has the same BSF’s slope, group delay, 3-dB beamwidth, and gain as its neighbouring LWAs.

2. The BSFs of two adjacent LWAs should be designed with an angle difference of 6-dB beamwidth as shown in Fig. 3(b). This can be equivalently interpreted as a 6-dB beam-crossover regarding the radiation patterns between two adjacent LWAs. If this is satisfied, the two received passband spectrums from the two adjacent LWAs would be overlapped at 6-dB point. This is the so-called “magnitude stitching condition”, which is dedicated to synthesize a flat-while-widened spectrum bandwidth.

3. On the condition of satisfying the “magnitude stitching condition” mentioned above, a “phase stitching condition” should also be satisfied to ensure that one LWA can be coherently superposed with its adjacent LWAs in terms of the received signal spectrums so as to synthesize a bandwidth-enhanced spectrum in the backend module. How much the phase should be compensated mainly depends the group delay of LWAs and bandwidth of the overlapped spectrum (recall the 6-dB frequency point), as revealed in Fig. 3(a). This phase alignment process can be done in either RF analog or baseband digital domain.

If all of the design assumptions and specifications described above can be met, the relationship between the range and angle resolutions can be modified as

\[
\Delta R \cdot \Delta \theta = \frac{c}{2\sqrt{2N}} s',
\]

and an expanded and stitched frequency-space domain coverage would be formed for radar operations as plotted in the right-hand side of Fig. 1(b). Clearly, for an FMCW radar configured with an FB-enabled array of \(N\) Rx LWA channels that possess a certain 3-dB beamwidth (angle resolution) and beam-scanning rate, the range resolution could be improved by a factor of \(\sqrt{2N}\). Alternatively, for a certain range resolution that has been predetermined, a refined angle resolution (narrowed 3-dB beamwidth) can be realized at the expense of the deployment of more LWA channels. In this respect, it can be said that the proposed FB-enabled LWA array solution for FMCW radars has a competitive design freedom compared to the traditional phased-array-related counterpart in terms of the range and angle resolutions.

III. A PROOF OF CONCEPT

There are several points that should be highlighted here before conducting a verification of this proposed FB-enabled multiple-channel LWA array solution. Firstly, our proposed solution mainly lies in a delicate engineering of an array of LWAs in accordance with several specifications such as BSFs, beam-crossovers, and phase alignments. The main body of a practical system architecture of our proposed solution can be almost the same as that of the traditional multi-channel FMCW radar [10] except for the antenna front-end and signal-processing module. Secondly, the success or failure of the required “frequency-space stitching” for radar operations is directly under the premise of whether or not the LWA array can be properly engineered or synthesized as required. More specifically, if a stitched frequency-space domain could be realized for radar operations, the whole FB-enabled LWA array must present a widened radiation pattern (spatial stitching) at given frequencies and enhanced gain bandwidth (spectral stitching) towards given directions. This is to inspect the “frequency-space stitching” phenomenon from the point of the antenna, which may give us a convenient and straightforward way to examine the effectiveness of the LWA array engineering. Under this background, as a first-step and direct demonstration of the proposed solution, a two-element FB-enabled LWA array is developed and presented in the current stage. It should be noted that the proposed FB-enabled LWA array solution requires that the LWA candidate should embrace stable radiation performances such as gain and beamwidth with frequency, as well as possess a linear or quasi-linear BSF. To roughly meet these requirements, the candidate LWA element is selected from our previous work [11], which is a periodic type microstrip combine LWA that uses the multimode-resonator (MMR) design concept for radiation stabilities. By properly selecting the period-length and quantity of unit-cells, an engineered BSFs and beam-crossovers can be approximately realized for this LWA array. Notably, for simple demonstration purposes the two LWAs are combined in the RF analog domain through an SIW two-way power divider/combiner that incorporates a delay line for the
a flat and widened passband signal spectrum. Obviously, there is a constant phase difference in the overlapped spectrum region between the two received passband spectrum, which can be roughly compensated by a delay-line as incorporated in the SIW power divider/combiner. Under this situation, the two received signal spectrums from the two LWA elements can be coherently superposed, thereby presenting a beamwidth-widened radiation pattern and enhanced gain bandwidth as exhibited in Fig. 5(c) and (d), respectively.

IV. CONCLUSION

In this work, an enabling technique inspired from the FB concept and embodied in an array of LWAs has been proposed and investigated for potential FSR applications with decoupled range and angle resolutions. The proposed solution artfully makes a combination of the natural frequency-based beamscanning inherently owned by LWAs and the FB concept borrowed from multi-rate signal processing field to realize a stitched frequency-space domain and full-band coverage for radar operation. The critical “frequency-space stitching” phenomenon has successfully been verified from the perspective of an antenna, thereby justifying the effectiveness of this solution. Compared to the prevailing phased array technique, the virtues of our proposed LWA array-based scheme are distinct: it is shifter-less and wideband, and the angle and range resolutions can be designed with a great degree of freedom for radar detection and sensing. For example, more priorities can be given to the angle resolution without using a plenty of Rx channels. As a result, the proposed scheme may be a potential candidate solution to be deployed in current and future radar applications.

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