Frequency Invariant Far-Field Beam Pattern of UWB Printed Circular Monopole Antenna Array

Zainul Ihsan, Klaus Solbach
University Duisburg-Essen, Hochfrequenztechnik, Duisburg, D-47057, Germany

Abstract—This paper applies the concept of the frequency invariant far-field beam pattern to a printed linear UWB antenna array. The theory of the broadband frequency invariant far field sensor from the field of acoustics is adopted and applied to a discrete UWB printed circular monopole antenna array (PCMAA) for the frequency range from 3.1 to 10.6 GHz. Low pass filters (LPF) are employed to feed the individual elements of the PCMAA in order to establish an array of frequency invariant electrical width. Although the array design deviates from the ideal design by using uniform element spacing, the full wave simulation and the measurement verify that the variation of the beamwidth across the frequency range can be suppressed by filtering the PCMAA element excitation with a set of LPF.

Index Terms—UWB antenna array, printed circular monopole antenna, frequency invariant beam pattern.

I. INTRODUCTION

UWB radio is a fast emerging technology with uniquely attractive feature inviting major advances in wireless communication, networking, radar, imaging, positioning system. It has drawn a great attention specially since FCC released a spectral mask operation of the UWB radio over 7.5 GHz bandwidth with very low power level (below -43 dBm) that can provide high-rate data transmission above 110 MB/s over a short range (10-15 m) [1].

An advanced technical approach is necessary due to the low power level requirement. Regarding to the antenna aspect, one approach to improve the link budget of such a short range communication could be to focus the radiation towards certain direction using an array antenna. A problem associated with an array antenna is that the beamwidth decreases with frequency (and gain increases) which could be solved by an array design providing a frequency invariant antenna pattern.

Planar UWB antennas have drawn great interest due to compact size and low cost and can be successfully implemented as linear arrays [2-4]. On the other hand, some ideas to achieve frequency invariant beam pattern for wideband antenna arrays have been proposed in the literature. One example is a rectangular array of monopole antennas with integrated attenuators as the weighting factors applied to each element working across the 1.9-2.5 GHz frequency range [5]. Another example is a circular array of mono cone antennas which are fed by FIR filters for frequencies of 1.5-2 GHz [6].

The aim of this paper is to present a design for a printed UWB antenna array for 3.1-10.6 GHz with frequency invariant far-field beam pattern. The design is based on the theory of the discrete sensor array as an approximation of a continuous sensor distribution as developed in the frame of acoustic technology. The design was implemented as a planar circuit incorporating a UWB printed circular monopole antenna array.

II. THEORY OF BROADBAND FREQUENCY INvariant FAR-FIELD BEAM PATTERN

A. Discrete Broadband Omni Directional Array Sensor

Theory and design of a broadband array sensor with a frequency invariant beam pattern is presented in [7] and is summarized in the following. The theory starts out from of a continuous distributed sensor which is approximated in a discrete set of filtered broadband omni-directional array elements. The output of a linear continuously sensor aligned with the x-axis is defined as:

\[ Z_f = \int_{-\infty}^{\infty} S(x, f) \rho(x, f) dx \]

where \( S(x, f) \) is the signal received at a point \( x \) on the sensor due to the signal of frequency \( f \), and \( \rho(x, f) \) represents the sensitivity or gain at point \( x \) at frequency \( f \). A sensitivity distribution (2) as given by a product of frequency \( f \) and a complex valued function \( G \) of \( xf \)

\[ \rho(x, f) = fG(xf) \]
can be shown to lead to a frequency invariant pattern. The output of the sensor can then be represented as

\[
Z_f = \int_{-\infty}^{\infty} S(x, f)G(xf)dx
\]  

(3)

For a discrete array, the integral in (3) can be approximated by the numerical approximation, given as

\[
\tilde{Z}_f = f \sum_{i=0}^{N-1} S(x_i, f)G(x_i f)
\]  

(4)

where \(\tilde{Z}_f\) represents the output of the discrete sensor, \(N\) is the number of the discrete sensors, \(S(x_i, f)\) is the sample signal received by sensor \(i\) at point \(x_i\) at frequency \(f\), and \(G(x_i f)\) represents the sensitivity (gain) function sampled at \(x=x_i\).

The sensitivity function \(G(x_i f)\) of a frequency invariant sensor at \(x_i\) is understood as the primary frequency response (or filter) at this point and is set equal to \(H_x(f)\). Consider \(H_{\text{ix}}(f)\) is the filter response at point \(p\). For a linear array, due to phase dilation \(H_{\text{ix}}(f) = H_x(fx)\)

\[
H_{\text{ix}}(f) = H_x(x_i f)
\]  

(5)

and thus \(H_x(f)\) at position \(x_i\) can be represented as

\[
H_{x_i}(f) = H_x(x_i f)
\]  

(6)

Fig.1 shows the block diagram of a broadband discrete linear array. In realization, low pass filters (LPF) will be applied as the primary filter. In general, the position of the discrete sensor of the size \(Pk_1\lambda\) can be summarized as follows:

\[
x_i = \begin{cases} 
 k_1\lambda_u i, & \text{for } 0 \leq i \leq P \\
 P(k_1\lambda_u)(\frac{P}{P-1})^{i-P}, & \text{for } P < i < N - 1 \\
 P(k_1\lambda_u), & \text{for } i = N - 1
\end{cases}
\]  

(9)

Where the \(\lambda_u\) and \(\lambda_l\) are the wavelength of the lowest frequency \(f_l\) and the highest frequency \(f_u\) respectively. According to the sensor position, the cut-off frequency of the LPF connected to sensor-\(i\) is expressed as

\[
f_i = \frac{Pk_2c}{x_i}, \quad i \in \{0, 1, ..., N - 1\}
\]  

(10)

where \(c\) is the speed of light and \(N\) is the total number of the discrete sensors. We introduce the coefficient \(k_2\) as the coefficient of the filter cut off frequency that determines the beamwidth and the length of active sensor. If the value of \(k_2\) is equal to \(k_1\), the length of the active sensor at the wavelength \(\lambda\) is equal to \(Pk_1\lambda\).
Fig. 2a shows the contour plot of the normalized beam pattern for the UWB frequency range for an array design based on this theory; the parameters are chosen as: \( P = 6 \), \( N = 13 \), \( k_1 = 0.7 \), \( k_2 = 0.7 \), \( f_L = 3.1 \, \text{GHz} \), \( f_U = 10.6 \, \text{GHz} \). According to (9), this design results in uniform spacing at the inner elements and non-uniform spacing at the outer elements. The outer elements are active at the lower frequencies and are spaced such as to just avoid the arising of a grating lobe.

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The 12th order Butterworth LPF are assumed with the cut-off frequencies calculated based on (10). The main beamwidth seems constant across the UWB band and scanned to 19° which is due to the variation in the group delay of the filters (depending on cut-off frequencies); the beam scan can be compensated by insertion of suitable delay line. The figure also shows an increased sidelobe right to the main lobe which was found to be due to the phase error in the excitation of the array elements caused by the sloping variations in the LPF responses near cut-off frequencies. The single increased side lobe level is not present if idealized low-pass filters are used with abrupt cut-off behavior, as demonstrated in Fig. 2b.

### III. EIGHT ELEMENT PRINTED CIRCULAR MONOPOLE ANTENNA ARRAY AND FEED NETWORK

A four-element printed circular monopole antenna array (PCMAA) was introduced in [8]. Due to the dependence of the pattern on the element spacing, the beamwidth varies with frequency. The theory described in section 2 was applied to an 8-element PCMAA to realize a frequency invariant beam pattern. The minimum spacing between the sensors (elements) is restricted by the width of the single radiator, namely 46 mm. The design parameters are \( P = 6 \), \( f_U = 6.5 \, \text{GHz} \), \( k_1 = 1 \), \( k_2 = 0.7 \), \( N = 8 \). With this set of parameters, an eight element linear array with equal spacing of 46 mm was realized where the variables \( k_1 \) and \( f_U \) have to be adapted to adjust the minimum array spacing to the width of the single radiator. In addition, a set of delay lines is inserted to compensate the filter delay. To estimate the pattern of 8-element PCMAA, the array factor of such a configuration is calculated and depicted in Fig. 3 where the beam width seems constant and centered at the broadside.

However, apart from increased sidelobe levels at the right side of the main beam, a grating lobe...
arises at 6.5 GHz due to the spacing (larger than \( \lambda \) above 6.5 GHz).

As a verification of theory, the 8-element PCMAA was fabricated as shown in Fig.4. A set of microstrip line stub LPF is inserted in the feed network of the PCMAA and a set of suitable microstrip delay line is added to shift the beam to the center. A three stage Wilkinson power divider is used to feed the PCMAA which provides isolation between the output ports, necessary to compensate the reflection from the filters (at frequencies above cut-off). Peak reflection coefficient values were measured up to -7 dB while average return loss found better than -10 dB across the band. Fig.5 and Fig.6 show a good agreement between full wave simulation [9] and the measurement. The inserted filters result in a frequency invariant beam width over most of the UWB frequency range even though there was found slight variation of the absolute gain due to the loss, imperfect matching and low number of the discrete elements. The grating lobes appear less pronounced than in the simulation using isotropic radiators (Fig.3) due to the directive element pattern of the printed circular monopole which partly suppresses the grating lobes.

IV. CONCLUSION

The theory of frequency invariant antenna beam pattern for UWB frequency has been applied to design an 8-element printed circular monopole antenna array with frequency invariant beam pattern. Simulation and measurement results show that the beamwidth can be kept constant by inserting a set of LPF in the feed network.

REFERENCES