Design and Performance Analysis of Wide angle Microwave Lens for Wireless Communication

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ABSTRACT
This paper presents analysis of non-focal Rotman lens antenna design. A ten beam prototype feeding an 20-element antenna array working in ISM band has been simulated using RLD v1.7 software. Simulation results show that the designed lens shows good performance in the operating frequency band of 2.4Ghz showing a return loss of -17db.

Keywords
Array factor, side lobe level beam ports, array ports, scanning angle, focal ratio, return loss.

1. INTRODUCTION
The ability to simultaneously scan multiple beams of the antenna array is of very important in many applications. Due to the developments in the wireless communication technology, smart antenna arrays which support multi beams [1] are capable of providing wide angle scanning over a broad frequency range. Numerous applications include satellite communications,Radar systems and many military based applications. In order to achieve reliable, low cost, multi beam phased arrays, the Rotman lens is an attractive candidate in this category. It is reliable beam-forming network, as the mechanical scanning and electronic scanning with phase shifters can be very costly. The popularity of Rotman lens for many electronic scanning applications is due to its simple design and compact size. They are used in many electronic scanning applications due to simple, compact design and low cost. Scanning approach controls the relative phase values at the array elements using microwave lens structures achieving the desired progressive phase shifts through time delay[3,4,5]. W.Rotman and R.Turner first proposed the Rotman lens which consists of air filled parallel conducting plates fed by co-axial probes [1]. D.Archer [2] gave a modified design of Rotman lens in which a dielectric material is filled between parallel conducting plates fed by microstrip lines. Rotman lens provides linear phase shifts at the output ports by utilizing different propagation paths within the lens structure[6,7].

Rotman lens is based on true time delay and has multibeam capability.The original Rotman lens which was proposed had three focal points along the 2D curve determined by three simultaneous equations [1]. These equations determine the position of inner receiving contour and the transmission line path difference which is essential parameter of determining the Rotman lens structure. Based on the same principle several modified trifocal lens have been investigated. Design of physical structure at high microwave frequencies is challenging issue. Also at low frequencies the Rotman lens realization becomes quite larger and so it is difficult to integrate it in compact transceiver designs[7,8,9].

In this paper Rotman lens is proposed which has got the scanning capability of angle $\pm 40^{\circ}$ and has a medium of dielectric constant of 4.4 in between the two contours. The centre frequency of lens is 2.4GHz which is also called the ISM band or Industrial Scientific and Medical Band which is a licence free band. Design of the lens is adapted from the formulas found in [1] and [10]. Simulations were carried out using RLD 1.7 designer software and various performance analysis parameters such as array factor, insertion loss, S-parameters and phase error are analysed to prove the effectiveness of the proposed Rotman lens design for wireless communication.

This paper is organized as follows: Section II presents lens design approach in which the Rotman lens design equations and its important design parameters are discussed. Section III presents a design example of Rotman lens. In section IV simulation results of the designed Rotman lens are presented and finally in section V conclusions are drawn.

2. LENS DESIGN APPROACH
Fig.1 shows a schematic diagram of a trifocal Rotman lens. Input ports lie on contour C1 and the output ports lie on contour C2. C1 is known as beam contour and C2 is known as array contour[1,10,11,12]. There are three focal points namely F1, F2 and F3. F1 is located on the central axis while F2 and F3 are symmetrically located on the array contour at an angle of +α and – α respectively. It is quite clear from Fig.1[1,10] that the co-ordinates of two off-axis focal points F2, F3 and on one axis focal point F1 are (-f2cosα, f2sinα), (-f2cosα, f2sinα) and (-f1, 0) respectively.

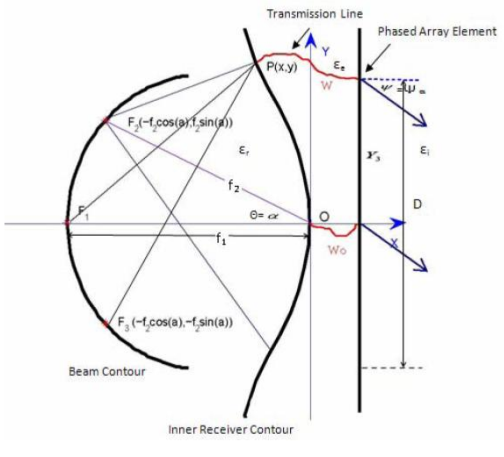

Fig.1 Trifocal Rotman Lens Schematic Diagram.

where

f_1 -On axis focal length

f_2 -Off axis focal length

α -Off center focal angle

ψ_α -Scanning angle

$\gamma = \dfrac{\sin\psi}{\sin\alpha}$ - beam angle to ray angle ratio given as ratio of sine of their angles.

ε_r -Permittivity of medium in between the lens contour

ε_e - Permittivity of medium of transmission line

ε_i -Permittivity of medium of radiating element

$\beta = \dfrac{f_2}{f_1}$ -Focal ratio

w_o - Transmission line length between axis point 'O'and radiating element.

w -Transmission line length between point 'P'and radiating element.

FiP-It is the physical distance from focal point Fi to P.

ξ is another important parameter that relates the distance Y_3 of any point on the array contour from the axis, to f_1. ξ controls the portion of phase and amplitude error curves that the lens experiences [4].

It is given by- $\xi = \dfrac{Y_3 \gamma}{f_1}$.

If we assume that the ideal focal points are located at $\theta = \pm \alpha$ and 0, and their corresponding radiation angles are $\Psi = \pm \Psi\alpha$ and $\Psi = 0$, given $\Psi\alpha$ is a known angle, simultaneous equations 1-3 are satisfied:

$$F_2P\sqrt{\varepsilon_r} + w\sqrt{\varepsilon_e} + Y_3\sqrt{\varepsilon_i}\sin\psi_\alpha = f_2\sqrt{\varepsilon_r} + w_o\sqrt{\varepsilon_e} \text{--------(1)}$$

$$F_3P\sqrt{\varepsilon_r} + w\sqrt{\varepsilon_e} - Y_3\sqrt{\varepsilon_i}\sin\psi_\alpha = f_2\sqrt{\varepsilon_r} + w_o\sqrt{\varepsilon_e} \text{--------(2)}$$

$$F_1P\sqrt{\varepsilon_r} + w\sqrt{\varepsilon_e} = f_1\sqrt{\varepsilon_r} + w_o\sqrt{\varepsilon_e} \text{----------(3)}$$

Also we have-

$F_2P^2 = (-f_2\cos\alpha - X)^2 + (-f_2\sin\alpha + Y)^2$ ------------(4)
$F_3P^2 = (-f_2\cos\alpha - X)^2 + (-f_2\sin\alpha - Y)^2$ ------------(5)
$F_1P^2 = (f_1 + X)^2 + (Y)^2$-----------------------------(6)

By algebraic manipulation of the above equations we can obtain geometric lens equation [1, 10, 16] which is quadratic in nature and is given by-

$$a.\frac{\varepsilon_r}{\varepsilon_e}.W^2 + b\frac{\sqrt{\varepsilon_r}}{\sqrt{\varepsilon_e}}.W + c = 0 \text{ ---------------(7)}$$

Where-

$$a = 1 - \frac{(1-\beta)^2}{(1-\beta C)^2} - \frac{\varepsilon_i \xi^2}{\varepsilon_r \beta^2}$$

$$b = -2 + \frac{2\varepsilon_i \xi^2}{\beta \varepsilon_r} + 2\frac{(1-\beta)}{1-\beta\cos\alpha} - \frac{\xi^2 S^2 (1-\beta)}{(1-\beta C)^2}\frac{\varepsilon_i}{\varepsilon_r}$$

$$c = -\xi^2 + \frac{\xi^2 S^2}{(1-\beta C)} - \frac{\xi^2 S^4}{4(1-\beta C)}\frac{\varepsilon_i}{\varepsilon_r}$$

W -Normalized relative transmission line length and is given as $W = (\dfrac{w - w_o}{f_1})$.

S=sinα and C=cosα

It is important to note that the number of beams, number of elements, maximum beam angle and element spacing are known from the system requirement and so the task is to select the optimum values of α, β, γ and f_1/λ [10,11,16].

Element spacing d is also very critical as it controls the appearance of grating lobes. The spacing that just admits a grating lobe is given by-

$$\frac{d}{\lambda} = \frac{1}{2 + \sin\psi_m} \text{ ------------------------(8)}$$

where Ψ_m is the maximum beam angle.

3. DESIGN EXAMPLE

The Rotman lens is designed in microstrip configuration to meet the following specifications: Angular coverage= ±40°, number of antenna elements=20, number of input beams = 10, central frequency = 2.4GHz. The lens structure is fabricated in a microstrip version on a substrate of thickness 1.542mm and dielectric constant of 4.4. The loss tangent is 0.001. In order to have perfect operation of the lens, reflections within the lens must be avoided. In microstrip configuration this is obtained by employing dummy ports. The designed lens is shown in fig. 2.Input beam port 5 is excited and other input ports are kept at low potential to avoid interference of the signals amongst various ports.

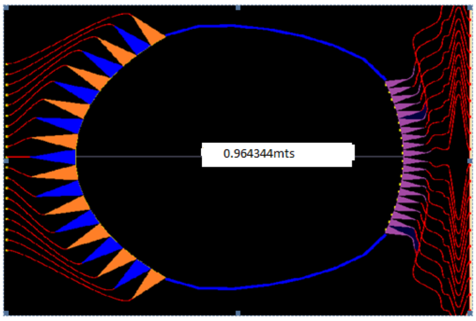

Fig.2 Simulated Rotman Lens

4. SIMULATION RESULTS

The Rotman lens with the specifications mentioned in section III is designed and simulated using RLDv1.7 software. The array factor pattern is shown in Fig.3 .Input beam port 5 is excited and it is quite clear from the plot that good results are obtained in terms of both the side lobe level and main lobe direction. There is only one main lobe. The side lobe level and the unwanted grating lobes are also well below the desired level.The side lobe is at -14db and continues to fall below -25db

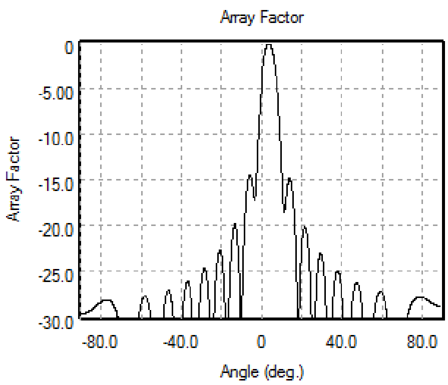

Fig.3 Array factor plot

As observed from the plot given in the fig.4,if the beam port is shifted from port 3 to port 10,the level of the grating lobes and the side lobes increases beyond the desirable limits.

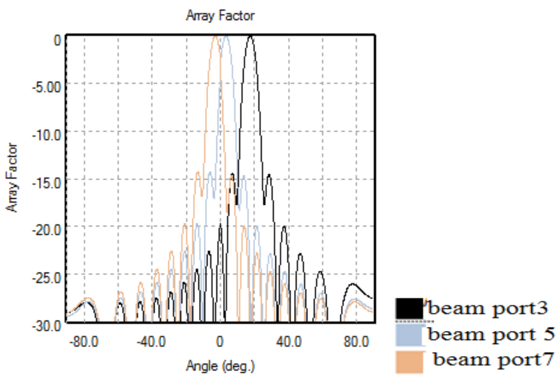

Fig.4 Array factor when Input beam port3,5 and 7 is activated

The desirable value of sidelobes are achieved when the input is provided to beam port 3, 5 or 7 as shown in fig.4

The beam to array phase error is shown in Fig.5. Phase error across the aperture takes place for each beam port excitation. In this case beam port 5 is excited at 2.4GHz. It is observed that the phase error falls from array port 11 to array port 20 and then there is a rise in the phase error form port 21 to 30

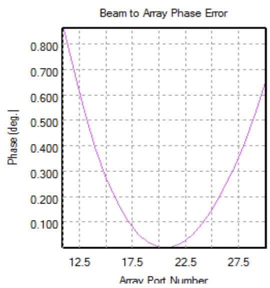

Fig.5 Beam to array Phase error

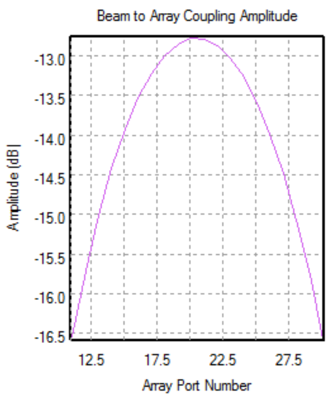

Fig.6 Beam to array coupling amplitude with beam port 5 activated

As observed from fig.6 the best coupling magnitude is between beam port 5 and array port 20 of -12dB.It shows good coupling between the input and the output ports.The table I below shows the phase error and coupling magnitude between various ports.

Table I: Representation of phase error and coupling magnitude

Array Port No.	Phase in degrees	Beam to array coupling magnitude(dB)
10	0.85	-16.6
15	0.3	-14
20	0	-12.5
25	0.15	-13.5
30	0.65	-16.6

Fig.7 shows the variation of S-parameters with frequency. The value of return loss when beam port 5 is activated is given as S5_5 which is -12.34db. **Return loss** is the loss of signal power when transmitting any kind of voice or data signal in the network. **VSWR** (Voltage Standing Wave Ratio) is a term which is related to how well the impedances of the antenna, radio and other RF Path equipment are matched.

Return loss is calculated as $|\Gamma| = \frac{VSWR-1}{VSWR+1}$

Reflected power in (dB) $= 10\log|\Gamma^2|$

$= 20\log|\Gamma|$

Reflected power in (%) $= 100(\Gamma^2)$

Nonreflected power or delivered power is calculated as

$$|\tau^2| = 1 - |\Gamma^2|$$

Mismatch loss (dB)= $10\log_{10}\left(|\tau^2|\right)$

$= 20\log_{10}(\tau)$

$= 10\log_{10}\left(1-|\Gamma^2|\right)$

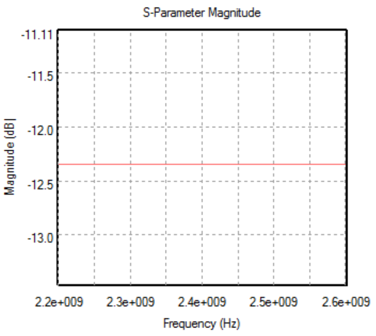

Fig.7 S-parameter(S5_5) magnitude vs .frequency

For the designed system the value of
VSWR=1.12
% of power Reflected =0.3
Reflected power in (dB) = -24.94dB
Amount of power lost due to impedance mismatch (dB) =0.01

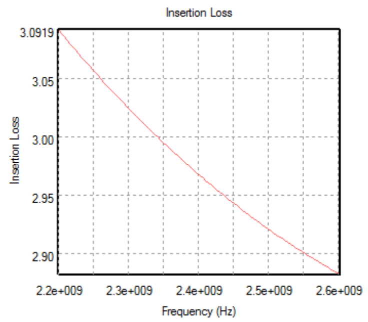

Fig.8 Insertion loss for excitation at beam port 5

Fig.8 represents the insertion loss.The insertion loss is calculated by summing the received powers at the array and beam ports, relative to the transmitted power of each beam. The insertion loss is calculated by

$$L_k = -10 \log \sum_n |S_{nk}|^2$$

This is the insertion loss corresponding to beam port k where n is the index for the array ports. Fig 8 shows the insertion loss variation for beam port 5 in the operating frequency band of 2.4GHz is 2.96dB. Table II represents the magnitude of return loss and insertion loss.

Table II: Return loss and insertion loss

Return loss	-12.34dB
Insertion loss	2.96dB

5. CONCLUSIONS

A design approach for the Rotman Lens has been presented. An ISM-band lens prototype with ten beam ports feeding twenty-element array has been simulated. The simulated lens has shown very good performance in terms of array factor, S-parameter values, beam port to array port coupling magnitude and also exhibits low phase errors. The design shows that the reflected power is only 0.3% and rest of the power is transmitted through. Future work will focus on further reducing the phase error, return loss and also enhancing the scanning capability of the Rotman lens.

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