smooth curvature at the output. There are a variety of options in choosing the shape of the receiving contour. We choose an elliptical arc because it resembles the shape in a conventional Rotman lens. As shown in Fig. 3, we have 24 variables to optimize, which include the coordinates of input ports ($x_{f1} \dots x_{f3}$, $y_{f1} \dots y_{f3}$), y-coordinates of output ports ($y_1 \dots y_8$), radii of elliptical receiving contour (l_1, l_2) and corresponding delay line lengths ($w_1 \dots w_8$). For cases with higher number of input or output ports, the number of optimization variables increase, which would inevitably slow down the convergence of the PSO to good solutions.

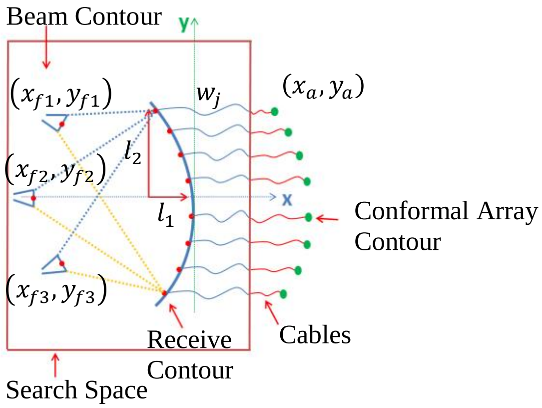

Fig. 3. Concept of non-focal lens design.

The fundamental challenges of this problem are how to design a lens so that it not only supports a conformal array, but is also practical for fabrication. Thus, we must implement a suitable cost function in PSO to guarantee a smooth curvature, and to position all output ports well for maximum power reception. Below are the constraints we choose for the PSO algorithm to design an appropriate lens:

i. Ports are randomly distributed on the receiving contour with spacing requirement $\boldsymbol{\lambda_r/2 \le S_i \le 3\lambda_r}$ where $\boldsymbol{\lambda_r = \lambda/\sqrt{\varepsilon_r}}$ is the effective wavelength inside the substrate, and $\boldsymbol{S_j}$ is the arc length between two adjacent output ports $\boldsymbol{(x_j, y_j)}$ and $\boldsymbol{(x_{j+1}, y_{j+1})}$. The minimum spacing between two adjacent ports is $\boldsymbol{\lambda_r/2}$ to make sure that it is posible for the lens to be fabricated while the maximum spacing is $\boldsymbol{3\lambda_r}$ constrains the overall dimensions of the lens.

ii. Beam ports are positioned randomly with a constraint on the minimum distance between each pair, such that $\boldsymbol{d_i} = \sqrt{\left(\boldsymbol{x_{fi} - x_{fi+1}}\right)^2 + \left(\boldsymbol{y_{fi} - y_{fi+1}}\right)^2} \ge \frac{\lambda_r}{4}$. Unlike the conventional lens, our approach has no limitations for the beam ports to lie on a circular or elliptical arc.

iii. An important constraint is to make sure beam ports do not block each other. We define an illuminating region from a beam port to the output ports (the regions are separated by the dashed blue and solid yellow lines as shown in Fig. 3). If the other input ports happen to lie in this region, the PSO algorithm will not accept these cases as solutions.

VI. PERFORMANCE OF PSO

After all the constraints are satisfied, the phases at the output ports are calculated and compared with the set of desired phase values to assess the cost function for this optimization problem. We use 600 agents and a maximum of 10000 iterations, where the user defined variables are chosen as $c_1 = c_2 = 2$ and $w = 0.9$. The optimization aims to minimize the cost function (3):

$$F = \sqrt{\sum_{i=1}^{N_{input}} \sum_{j=1}^{N_{output}} \left(\phi_{i,j} - \phi_{i,jref}\right)^2}, \qquad (3)$$

where $\phi_{i,j}$ is calculated in (2) and $\phi_{i,jref}$ is the desired phase values. To limit the overall dimensions of the lens, we set the search space for input ports, output ports and length of a delay line in appropriate intervals. For example, for a 3-input, 8-output Rotman lens, we would want $x_{fi} \in [-10\lambda_r, 0]$, $y_{fi}, y_j \in [-10\lambda_r, 10\lambda_r]$, $a, b \in [4\lambda_r, 10\lambda_r]$, $w_j \in [\lambda_r, 10\lambda_r]$. Figure 4 shows the convergence rate of the optimized lens in case 1 and 2 over 10000 iterations.

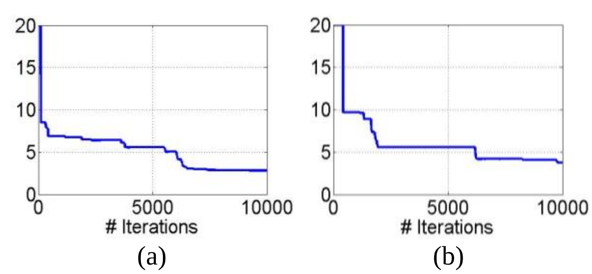

Fig. 4. Performance of PSO for optimized lens in case 1 and case 2.

VII. RESULTS FOR NON-FOCAL LENS

To verify the robustness of our lens design, we design a 3-input, 8-output used to feed a slightly bent conformal array with parameters specified in case 1 and case 2, Table 1. The substrate we are using is Duroid 5880 with $\varepsilon_r = 2.2$. Figures 5, 6 show the simulation model of the lens using commercial software package FEKO and its performance over a bandwidth from 9 GHz to 11.5 GHz. Figures 7, 8 show the radiation pattern of the array fed by the output of the lens at 10 GHz.

The overall dimensions of the non-focal lens design in each case are greater compared with the conventional Rotman lens working at 10 GHz and using the same substrate.

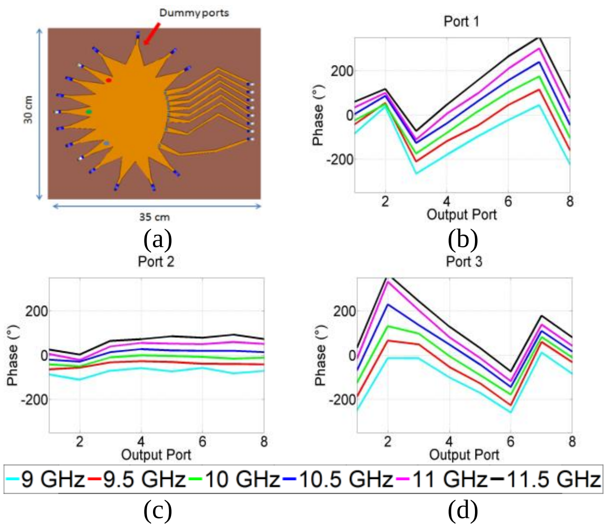

Fig. 5. 3-input, 8-output lens to feed conformal array in case 1: (a) CAD model, phase performance, (b) Port 1, (c) Port 2, and (d) Port 3.

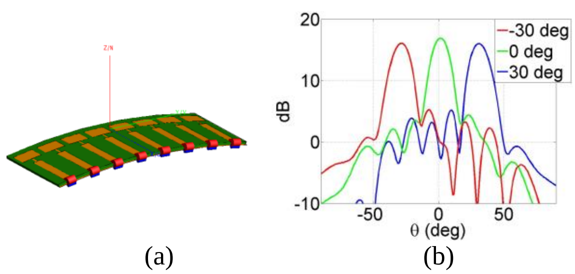

Fig. 6. (a) Bent array in case 1, and (b) radiation pattern of the array at -30°, 0°, 30°.

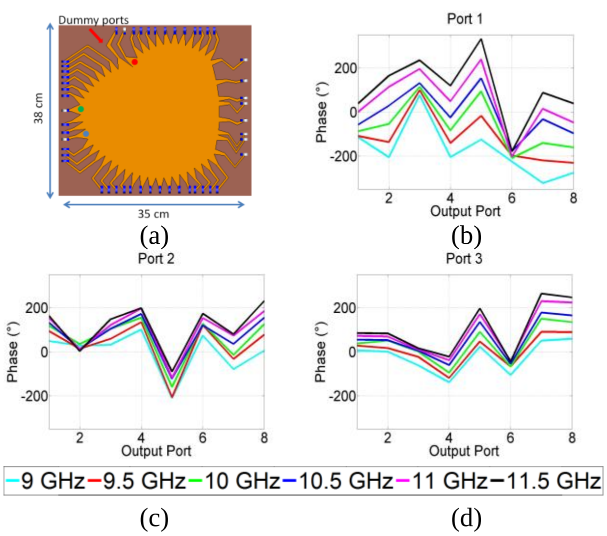

Fig. 7. 3-input, 8-output lens to feed conformal array in case 2: (a) CAD model, phase performance, (b) Port 1, (c) Port 2, and (d) Port 3.

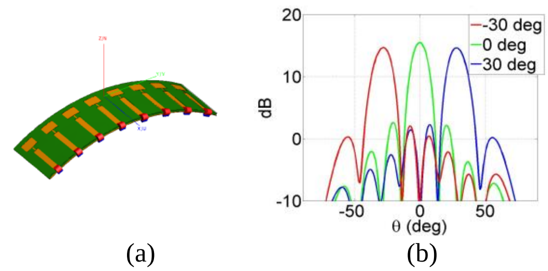

Fig. 8. (a) Bent array in case 2, and (b) radiation pattern of the array at -30°, 0°, 30°.

VIII. CONCLUSIONS

In this work, we investigated a new design technique to extend the design equations of Rotman lens to feed conformal array antennas. The applicability was shown using a cylindrical curvature, but the method applies to other curvatures as well. The results show that with similar total dimensions compared with conventional Rotman lens working at the same frequency and substrate, this lens design is able to support a cylindrical array. The proposed design works with any array antenna on different singly curved surfaces. While the concept has been shown for a 3-input port lens, the optimization can be run for higher number of input and output ports. However, for such cases, the number of optimization variables increase, which would inevitably slow down the convergence of the PSO algorithm to good solutions.

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