Automated Design of a 3D Printed Waveguide Surface Coupler

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Abstract—We have implemented an automated optimization algorithm which generates de-novo EM structures under specified design objectives. We demonstrated a particular design of a surface coupling antenna which is capable of launching energy efficiently into the main mode of a plastic waveguide. A 3D printer was used to print the designed system to verify our results. The maximum available power gain of the system was measured as 0.128, implying that the coupler achieves an efficiency of at least 36% at the designed center frequency of 9.6GHz. The actual coupler efficiency is believed to be much higher because the polymer used is very lossy in this frequency range.

I. INTRODUCTION

Plastic waveguide based serial links are recently emerging as efficient, cost-effective alternatives to traditional copper wire based systems. [1] Wireline links typically become extremely inefficient for distances approaching and surpassing 1m. While optical fibers can be efficient over long distances, optical links can be very expensive, do not integrate easily with standard CMOS processes, and require expensive alignment protocols. In contrast, plastic waveguides offer the advantages of low loss across medium distances (1-10m) and low integration costs since they can be excited electrically with metal coupling antennas. Unless the link is very long, the majority of the loss is dominated by the transmit and receive coupling losses. Furthermore, the overall power efficiency is the square of the individual coupler efficiency due to the TX and RX couplers. Therefore, it is crucial to utilize efficient couplers to transfer incident power effectively into the fundamental waveguide mode. In this paper, we discuss the design of a custom, optimized surface coupler, which is 3.5x more efficient than a standard dipole antenna, leading to a greater than 10x improvement in link efficiency.

II. OPTIMIZATION ALGORITHM

Our optimization algorithm works on a structured grid of unit cells which can either be filled in to represent a patch of metal or left empty. Due to mode profile symmetry, a good coupler should also be symmetric. We reduce the design space by optimizing one “wing” of the coupler and mirroring it for the other side. Since each cell can either be filled with metal or left empty, there are $2^N$ possible configurations for a grid of N cells. Given fixed waveguide dimensions, the number of cells that can be used is ultimately limited by the fabrication resolution. For our specific implementation we utilized a $13 \times 5$ cell grid per coupler wing which results in $2^{65} \approx 3.8 \times 10^{19}$ possible configurations. Due to the 0−1 nature of the problem, it can be shown that it is NP hard, meaning that no known algorithms exist which can guarantee finding a global minimum faster than an exhaustive search. Even for our relatively “small” design problem, going through $2^{65}$ designs would require an intractable number of EM simulations. Although it is a very difficult problem, many heuristic algorithms exist for attacking 0−1 problems including gradient based approaches and genetic algorithms. For our specific problem, finding a suitable gene crossover mechanism is tough and while we tried various techniques, none performed nearly as well as an even simpler optimization strategy: random coordinate ascent. At each iteration, we flip a random cell and keep the change if the performance improves, otherwise we revert the flip and repeat until convergence has been reached. We found that seeding the algorithm with a random solution performs best, although starting with “empty” and “full” designs yields acceptable results as well. We used our own custom FDTD-based 3D EM simulator coupled with some advanced techniques designed specifically for the specific problem at hand to optimize the ratio of the power coupled into the fundamental waveguide mode to the input coupler power at a single frequency. The resulting coupler is resonant because the optimization metric was enforced at a single frequency. Broadband couplers can be generated with multi-frequency objective functions. Fig.2 shows the ascent of the coupling efficiency vs. iteration for a typical run.
We used a Projet HD 3000 3D printer to print the link including the guide polymer (VisiJet Crystal EX 200) and the grooves for the coupler, which were filled with silver paste \((\sigma \approx 2.6 \times 10^9)\) as described in [2]. We optimized for a guide with cross-section close to \(\lambda \times \lambda/2\) where \(\lambda\) is the wavelength inside the material. The max resolution of the printer is \(\sim 200\mu m\), so we chose guide dimensions of \(18.8 \times 9.4mm\). This corresponds to a center frequency near \(9GHz\) in a guide with \(\epsilon_r = 3.2\). The dielectric properties are not provided by the manufacturer for the polymer used, but we were able to achieve a good match between measurement and simulation data by assuming values of \(\epsilon_r = 3.2\) and \(\tan\delta = 0.04\). These values seem reasonable according to measurements of other printer polymers at 10GHz. [3] 4-port S-parameters were measured with calibrated RF GSSG differential probes from 25MHz to 25GHz using a Agilent N5242A VNA.

III. DESIGN IMPLEMENTATION

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IV. MEASUREMENT RESULTS

The final design measured \(19.2 \times 9.5 \times 56mm\) and the couplers were spaced \(4mm\) from each end and measured \(18.8 \times 4.7mm\). Short feedlines connect the GSSG pads to the coupler feed-points. The measured S-parameters are converted to 2-port differential parameters and plotted in Fig.4. Since we targeted only coupling efficiency at \(9.6GHz\) in our algorithm, we compute the maximum available power gain at each measured frequency from the measurements and compare against HFSS simulation (Fig.5) The peaks between measurement and simulation line up closely. Discrepancies can be explained by uncertainty in the material properties. The link efficiency peaks to 13% at \(9.65GHz\). In a lossless system, this corresponds to a 36% coupling efficiency. However, the polymer and silver paste used are very lossy and we have noticed from our simulations that the majority of the losses come from the guide material, suggesting that the coupler itself is significantly more efficient and that a different plastic should be used for the next prototype. HDPE, for example, has been measured to have \(\tan\delta < 0.002\) at these frequencies and would make a good candidate for a second prototype.

V. CONCLUSION

We have developed a fast, yet simple optimization algorithm to design surface coupling antennas for dielectric waveguides de-novo and briefly detailed the main loop of the algorithm. In order to test the validity of the generated designs, we used a 3D printer to print the waveguides using polymer material and deposited silver paste for the coupler structures. Our measurement results match well with the HFSS simulated data and based on our simulations, we expect that we can achieve significantly improved link efficiency simply by switching to a different polymer material for the waveguide.

REFERENCES