A Simultaneous-Imaging Machine-Vision Approach for the Precision Alignment of Two mm-Wave Antennas

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Abstract— We present an optical imaging tool, the Overlay Imaging Aligner (OIA), developed to aid in the mechanical alignment of antenna components in the mm-wave and low-THz frequency regimes (50-500 GHz) where wavelength size poses significant challenges for alignment. A polarization-selective machine-vision approach used to generate two simultaneous overlaid images along a common axis allows for aligning two antenna components to within fractions of a wavelength. The concept and application examples are presented along with a quantitative assessment of the alignment accuracy in the WR-2.2 band where the OIA alignment is compared to an electrical alignment.

Index Terms— alignment, antenna, machine vision, mm-wave, terahertz, waveguide

I. INTRODUCTION

IN recent years more and more systems e.g. [1-4] are being developed in the mm-wave and terahertz frequency ranges. At these high frequencies (50-500 GHz), wavelengths can approach sub-millimeter dimensions. With such wavelength scales, the mechanical alignment of waveguide and antenna components becomes increasingly difficult. Antenna characterization techniques such as those used in extrapolation measurements [3,5], near field measurements [6-9] and general spatial antenna characterization require the precise positioning of antenna components. At these frequencies, new techniques must be developed for achieving the same alignment tolerances that has traditionally been straightforward to achieve in the MHz and lower GHz regimes. Although other alignment approaches using laser tracking systems have been previously proposed [10], in this letter we present a compact optical alignment tool that utilizes polarization-selective imaging to simultaneously capture and align, in real-time, two digital images of antenna components along a common axis, to within sub-wavelength precision and accuracy.

II. MOTIVATION AND CONCEPT

At the mm-wave and THz frequencies, the wavelength approaches mm to sub-mm dimensions. The resulting mechanical tolerances and position accuracy of mounts and alignment stages must be significantly better than half a wavelength, depending on accuracy requirements; i.e. tens to hundreds of microns.

An optical imaging tool using a polarization-selective machine-vision approach was developed at NIST-Boulder, CO

to address these alignment issues. This tool, the Overlay Imaging Aligner (OIA) provides real-time alignment of two waveguide or antenna components as well as mm-wave focusing and beam-shaping optics along a common axis, by overlaying simultaneous digital images of both components on a common imaging detector array.

The real-time simultaneous imaging of two antenna components is accomplished by generating two polarized images from the (assumed) unpolarized scene of the ambient or actively illuminated antennas. The OIA prototype system was designed to accommodate a field-of-view (FOV) suitable for aligning mm-wave antenna components. The optical components were chosen to obtain a transverse alignment precision of, $\Delta x = 52 \mu\text{m}$, which, at an operating frequency of 300 GHz, provides a precision of $\approx \lambda / 20$.

III. ANTENNA COMPONENT ALIGNMENT

A. Horn Antenna Alignment

The alignment images of two WR-03 pyramidal horns obtained with the OIA are shown in Fig. 1a, 1b. The alignment error is clearly visible in Fig. 1a, where the aperture of the horns, flanges, and precision alignment pins do not overlap. Figure 1b shows the antennas after adjusting the antenna mounts, where the alignment of the two antennas is clearly visible. The azimuth and elevation alignment of these horns was achieved by aligning multiple planes of the horns to the same axis.

Fig. 1. OIA image of two WR-03 pyramidal antennas showing, (a) overlapped misaligned horn images, and (b) horns after alignment where the image now appear as one single horn.

B. Lens Alignment to Horns

Precision lens alignment is achieved by imaging the horns through the optically clear TPX lenses with the OIA. The TPX lenses will act as magnifying glasses and produce magnified virtual images of the horn apertures. These virtual horn images act as virtual objects for the OIA optics, and can be re-

imaged by the OIA optics. Any misalignment of the lenses axes relative to the horn axes will appear as these virtual horns being misaligned.

Fig. 2. (a) Misalignment of “virtual horns” seen through TPX lenses with the OIA. (b) Both “virtual horns” are aligned and appear as overlapped and indistinguishable in the OIA image after lens alignment.

It is then a matter of aligning these virtual horns by adjusting the *TPX lenses* and *not* the actual horns. Figures 2a, 2b show the positions of the virtual horns before and after lens alignment.

A comparison of the OIA alignment to an electrical alignment was also made. The transmit horn position T_x was moved in 10 μm steps over a range of ± 200 μm , with 0 μm referencing the position that had been determined by alignment using *only* the OIA. The value of T_x that was needed to peak the power out of the receiver gives a measure of how far off from peaked electrical alignment the OIA achieves. Data for frequencies, 380 GHz, 400 GHz, and 450 GHz are shown in Fig. 3 where $|S_{12}|$ has been normalized by $|S_{12}|$ at $T_x = 0 \mu\text{m}$. These data show extremely good alignment accuracy obtained with the OIA, with errors in the relative peak electrical alignment transmitted power $\ll 0.1$ dB and discernable antenna position errors of $\Delta x \approx 50 \mu\text{m}$, as shown by the vertical dotted line in Fig 3.

Fig. 3. Receive power normalized to the OIA alignment position at 0 μm as a function of transmit horn position T_x for frequencies, 380 GHz, 400 GHz, and 450 GHz. Peak electrical alignment position is shown by the vertical dotted line.

IV. CONCLUSION

In this paper, we presented an optical imaging tool, the Overlay Imaging Aligner (OIA), developed at NIST-Boulder, CO, to aid in the alignment of antenna components in the mm-

wave and low-THz frequency regimes. The OIA uses a polarization-selective machine vision approach to overlay two simultaneous real-time images along a common axis, for aligning two antenna components to within fractions of a wavelength. The concept and application examples of the alignment of two WR-03 pyramidal horn antennas, as well as the alignment of a two WR-2.2 horn and TPX lens system are presented. Data over the 380-450 GHz range comparing the OIA alignment to an electrical alignment is presented demonstrating nominally obtainable transverse alignment accuracies of $\Delta x \approx 50 \mu\text{m}$ (i.e., $\lambda/16$ to $\lambda/13$).

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