OpenEM – Electromagnetic field mapping robot for microwave and RF measurements

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ABSTRACT

A low-cost, fully automated, electromagnetic field probing robot is described in this paper. The platform, called OpenEM Field Robot, is capable of mapping the spatial electromagnetic fields in free space. The system supports multiple antenna configurations and is scalable to large measurement domains. 3D printed antenna holders are also incorporated in order to allow for the near field measurements with minimal scattering and interference with the measurement. The goal of the system is to design a fully integrated platform for measuring electromagnetic fields that can be used with various other RF measurement devices and is configurable and easily modified for various applications in scientific research and education.

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Specifications table

Hardware name	OpenEM Field Robot
Subject area	• Engineering and Material Science
Hardware type	• Measuring physical properties and in-lab sensors
	• Field measurements and sensors
	• Electrical engineering and computer science
	• Mechanical engineering and materials science
Open Source License	CC-By Attribution 4.0 International
Cost of Hardware	$750 (Not including VNA/Antennas/Computer)
Source File Repository	https://osf.io/n3dpf/

1. Hardware in context

The characterization of RF and microwave devices often require the measurement of electromagnetic fields. Mapping the electromagnetic fields requires near field measurements at specific points in a measurement domain. Commercially

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available microwave measurement systems often require specialized robotics, antennas, and anechoic chambers to make measurements. An electromagnetic field mapping robot was constructed in order to characterize and visualize electromagnetic fields interacting with devices. Vector Network Analyzers (VNAs) are an important scientific instrument for the testing of RF/electromagnetic devices because of their ability to measure both the amplitude and phase of transmitted and reflected electromagnetic waves. For devices such as microstrips, coaxial connectors can be used to measure the S parameters of the device. Devices that require free space propagation, such as photonic crystals [1] and microstrip coupled meta-materials [3], require the use of antennas to make field measurements. A near field probe is required to spatially map the electromagnetic fields in space and can be used to measure the free space propagating fields, as well as near fields from devices such as microstrips and circuit boards [4–6]. The types of probes that can be used include dipole antennas, loop antennas, and monopole antennas. All of these provide different sensitivities and bandwidths depending on the frequency range, polarization, and also the environment. The device presented here expands upon the previous work on antenna characterization and is used to make electromagnetic measurements for research applications, which includes measuring both the spatial phase and amplitude of the electromagnetic wave. This is extremely important for characterizing microwave photonic devices, or any other device where the fields and phases need to be measured. For example, a 3D plasma photonic crystal has complex 3D fields and phases that can be manipulated and is very difficult to characterize using standard experimental microwave measurement techniques [2]. The OpenEM can provide full 3D measurement of the fields and phases for an arbitrarily large measurement domain and would be ideal for measuring such a system. The OpenEM platform allows the measurement of the electromagnetic field in 2D or 3D space and includes a full software suite to plot and visualize the fields.

2. Hardware description

The hardware for electromagnetic field measurements includes a two-axis rail and stepper motor, antenna mount, 3D printed microwave/RF probe, stepper motor controller and enclosure. Comparable commercial systems have similar components and capabilities, however often have proprietary software and hardware. In addition, the costs of these systems are oftentimes prohibitively expensive depending on the size and complexity of the setup, and require customized solutions that are not accessible in academic research environments. The hardware presented is designed for use for frequencies between 2 and 18 GHz, however can be modified for higher frequency RF signals. The system currently has a measurement area of 500 mm by 500 mm but can be expanded to larger areas by using longer rails. In addition, the system is designed to be used in laboratory environments that often require integration with other laboratory equipment, with the software suite programmed in LabVIEW. Additionally, the firmware for the stepper motors can be controlled using standard serial commands through USB. RF test equipment is able to be connected to the OpenEM measurement robot, with a vector network analyzer used to measure the amplitude and phase of RF signals at spatial points in 2D. The spatial mapping resolution can be as high as 0.2 mm, which can be useful for measuring high resolution fields near surfaces or interfaces. For larger measurement areas, it is typical to use resolutions of 0.5–2 cm, for a frequency range of 2–18 GHz. The included software has a smoothing feature of the VNA measurements to allow for better data visualization of the fields, especially for rough resolution measurements.

The probe consists of a 3D printed probe antenna holder for an SMA cable with an exposed inner conductor acting as a monopole antenna.

The OpenEM system has the following capabilities:

- The current system can be expanded to 3D with an addition of a third axis.
- This hardware was designed to be modifiable and expandable.
- This hardware uses open source motor controllers (Arduino) that can be integrated into any software system that has serial read/write capabilities.
- This hardware can be used with any microwave/RF measurement equipment and a wide range of frequencies.
- The antenna probe holders are 3D printed and can be customized for various applications.
- The spatial resolution of the measurements can be as high as 0.2 mm.
- The scanning distance is only limited to the size of the stepper motor rails.
- The software is compatible with any microwave and RF systems that can interface to a computer.
- The included data visualization software can process and visualize fields collected from the robot.

3. Design files

Design files summary

Design file name	File type	Open source license	Location of the file
probe_base.stl	3D Printing(.STL)	CC BY-SA 4.0	https://osf.io/nj5e4/
probe_stick_1.stl	3D Printing (.STL)	CC BY-SA 4.0	https://osf.io/t8yrh/
probe_thin_stick.stl	3D Printing (.STL)	CC BY-SA 4.0	https://osf.io/g5p4h/
probe_head.stl	3D Printing (.STL)	CC BY-SA 4.0	https://osf.io/gpbe7/
probe_head_2.stl	3D Printing (.STL)	CC BY-SA 4.0	https://osf.io/mnvby/
spacer_block.stl	3D Printing (.STL)	CC BY-SA 4.0	https://osf.io/fu7j5/
probe_stand.stl	3D Printing (.STL)	CC BY-SA 4.0	https://osf.io/5xa8w/
Field_Probe_Holder.pdf	PDF	CC BY-SA 4.0	https://osf.io/evnx7/
Motor_Box_Final.pdf	PDF	CC BY-SA 4.0	https://osf.io/pfmn9/
spacer_block.pdf	PDF	CC BY-SA 4.0	https://osf.io/4jwy8/
probe_stand.pdf	PDF	CC BY-SA 4.0	https://osf.io/xb5ke/
OpenEM_Run.VI	LabVIEW2014(.VI)	CC BY-SA 4.0	https://osf.io/89gr6/
Home_Stepper.VI	LabVIEW2014(.VI)	CC BY-SA 4.0	https://osf.io/5984g/
VNAMeasure.VI	LabVIEW2014(.VI)	CC BY-SA 4.0	https://osf.io/3hxjz/
Stepper_Move.VI	LabVIEW2014(.VI)	CC BY-SA 4.0	https://osf.io/5acgp/
LIFA_Base.ZIP	ZIP(Arduino Firmware)	CC BY-SA 4.0	https://osf.io/jdxhe/
VNA_DATA_CAL_6_12_18.zip	Python/Text Files	CC BY-SA 4.0	https://osf.io/94beh/
OpenEM_Operating_Instructions.docx	DOCX file	CC BY-SA 4.0	https://osf.io/5ga4v/

Design file name	Description
probe_base.stl	STL for probe base -3D Printed
probe_stick_1.stl	STL for probe stick 1 - 3D Printed
probe_thin_stick.stl	STL for probe thin stick - 3D Printed
probe_head.stl	STL for probe head orientation 1 - 3D Printed
probe_head_2.stl	STL for probe head orientation 2 - 3D Printed
spacer_block.stl	STL for spacer block part. Can be 3D printed, or fabricated using laser cutter.
probe_stand.stl	STL for probe stand. Can be 3D printed, or fabricated using machining.
Field_Probe_Holder.pdf	Laser cut file for field probe holder
Motor_Box_Final.pdf	Laser cut file for motor controller box
probe_stand.pdf	Technical drawing for probe stand part. Can me machined.
spacer_block.pdf	Technical drawing for spacer block part. Can me machined.
OpenEM_Run.VI	Main LabVIEW file for operating robot and collecting data
Home_Stepper.VI	Sub-VI for moving stepper – required in same folder as OpenEM_Run.VI
VNAMeasure.VI	Sub-VI for pulling data from VNA - required in same folder as OpenEM_Run.VI
Stepper_Move.VI	LabVIEW VI for moving stepper motors
Arduino_LIFA_Firmware	Firmware for Arduino - must be uploaded using ArduinoIDE to the CNC xPRO Controller V3
national_instruments_lib_labview_interface_for_arduino-2.2.0.79.vip	LabVIEW LIFA Firmware Drivers
VNA_DATA_CAL_6_12_18.zip	Contains data files that are the measurement results for the antenna from 2 to 18 GHz. Also contains Python script (VNA.py) for processing output from OpenEM_Run.VI. Allows visualization of fields.
OpenEM_Operating_Instructions.docx	Contains operating and setup instruction for OpenEM system.

4. Bill of materials

All cost are in USD ($)

Designator	Component	Number	Cost per unit - currency	Total cost - currency	Source of materials	Material type
C Beam Bundle	C-Beam Linear Actuator Bundle 500 mm	2	$117.99	$235.98	https://openbuildspartstore.com/c-beam-linear-actuator-bundle/	Metal/Other
Stepper Motor	NEMA 23 Stepper Motor	2	$27.99	$55.98	https://openbuildspartstore.com/nema-23-stepper-motor/	Metal/Other
Gantry Plate	V-Slot® Gantry Plate - Universal	1	$11.99	$11.99	https://openbuildspartstore.com/v-slot-gantry-plate-universal/	Metal/Other
Stepper Controller	CNC xPRO Controller V3	1	$119.99	$119.99	http://www.spark-concepts.com/cnc-xpro-controller-v3/	Other
Power Supply	CX500M ATX Power Supply	1	$89.99	$89.99	https://www.corsair.com/us/en/Categories/Products/Power-Supply-Units/cxm-series-config/p/CP-9020059-NA	Other
PLA Filament	PLA Filament 1.75 mm diameter	1	$29.99	$29.99	https://flashforge-usa.com/collections/filament/products/pla-filament-for-creator-and-creator-pro?variant=5344971653158	Plastic
¼" acrylic	Clear Cast Acrylic Sheet, 12" × 12" × 1/4"	1	$17.49	$17.49	https://www.mcmaster.com/#8560k354/=1dghu03	Plastic
Buna Gasket	Oil-Resistant Compressible Buna-N Gasket 1/8	1	$1.58	$1.58	https://www.mcmaster.com/#8516t138/=1dghxqh	Rubber
M5 Screw 20 mm	Low Profile Screws M5 - 20 mm	4	$0.15	$0.60	https://openbuildspartstore.com/low-profile-screws-m5-10-pack/	Metal
M5 Tee Nuts	Tee Nuts - M5	4	$0.29	$1.16	https://openbuildspartstore.com/tee-nuts-m5-10-pack/	Metal
SMA Cable	SMA Male to SMA Male Cable 36 Inch Length Using PE-P141 Coax with HeatShrink, LF Solder	1	$125.89	125.89	https://www.pasternack.com/sma-male-sma-male-pe-p141-cable-assembly-pe300-36-p.aspx	Other
¼" - 20 ½" Socket Head Screw	18-8 Stainless Steel Socket Head Screw 1/4"-20 Thread Size, 1/2" Long	50	$0.192	$9.61	https://www.mcmaster.com/#92196a537/=1dn6qys	Metal
¼" - 20 3/4" Socket Head Screw	18-8 Stainless Steel Socket Head Screw 1/4"-20 Thread Size, 3/4" Long	50	$0.217	$10.87	https://www.mcmaster.com/#92196a540/=1dn6qeo	
¼" - 20 Nut	18-8 Stainless Steel Hex Nut 1/4"-20 Thread Size	100	$0.0431	$4.31	https://www.mcmaster.com/#91845a029/=1dn6ogw	Metal
M4 × 0.7 mm Socket Head Screw	18- Stainless Steel Socket Head Screw M4 × 0.7 mm Thread, 10 mm Long	100	$0.0659	$6.59	https://www.mcmaster.com/#91292a116/=1doo63s	Metal
USB - A - USB B Cable	USB - A - USB B Cable 3 Ft	1	$1.02	$1.02	https://www.monoprice.com/product?p_id = 5437	Other

Tools: Soldering iron, drill press, end mill, Philips head screw drivers, hex drivers, hex wrenches.

The components in the C-Beam Linear Actuator Bundle 500 mm are included in the supplementary material (https://osf.io/sgvy5/).

5. Build instructions

5.1. X-Y linear actuator and Controller assembly

1. Carriage Assembly (Fig. 2). The carriage for the C Beam rail and stepper must be assembled. The carriage consists of a metal plate (C-Beam Gantry Plate) with a set of ball bearing wheels mounted on spacers. An 8 mm Metric Acme Lead Screw allows the carriage to me moved by the main lead screw that is connected to the stepper motors. Mount the 8 mm Metric Acme Lead Screw-250 mm to the carriage using two of the screws (Low Profile Screws M5-25 mm), with an Aluminum Spacer – 3 mm between the lead screen and the C-Beam Gantry Plate. Next, attach one set of the Eccentric Spacers – 6 mm to one side of the C-Beam Gantry Plate by pressing into the Gantry Plate according to (Fig. 2). Place two of the 1 mm Precision shims between the Mini V Wheel and the Eccentric Spacer and mount with the M5 Nylon Lock Nut and Low Profile M5-25 mm screws. Attach the second set of Mini V wheels using the 6 mm aluminum spacers and 2×1 mm precision shims and attach with the Low Profile M5-25 mm screw and M5 Nylon Lock Nut. Make sure that the wheels and bearings are free spinning and not over-tightened.
2. C Beam Rail and Stepper (2X) (Fig. 3) Assemble both of the C-Beam Linear Actuator Bundle 500 mm for both the x and y axis. Locate the 8 mm Metric Acme Lead Screw and attach a Lock Collar-8 mm on one of the ends, leaving ~0.5 in. of the end of the lead screw exposed. Place the ball bearing at the end of the lead screw and slide the lead screw into the C-Beam End Mount. Make sure the C Beam end mount is in the correct orientation such that the recessed hole is correctly fitted into the ball bearing of the lead screw. Attach the C Beam end mount to the C Beam Linear Rail using 4 of the M5 screws. Next, put the carriage at the other end of the lead screw through the Acme Lead Screw block so the carriage is coupled to the lead screw and turn the lead screw such that the carriage is in the middle of the lead screw and also the wheels of the carriage are corrected seated in the C Beam Linear Rail. Slide the second Lock Collar-8 mm and ball bearing on the other end of the lead screw, but do not tightened the lock collar. Attach the second C Beam end mount to the C Beam Linear Rail using 4 of the M5 screws. Pull the lock collar towards the C Beam end mount until the bearing is seated into the recessed bearing hole of the end mount and tighten the lock collar against the bearing. Turn the lead screw to make sure the carriage is properly seated to the rail and smoothly moves. Attach the ¼" flexible coupler at the end of the lead screw and tightened to the lead screw using the hex nut. Attach the Stepper motor to the flexible coupler and mount the stepper motor to the end of the C Beam end mount using the M5-55 mm screws and aluminum spacers.
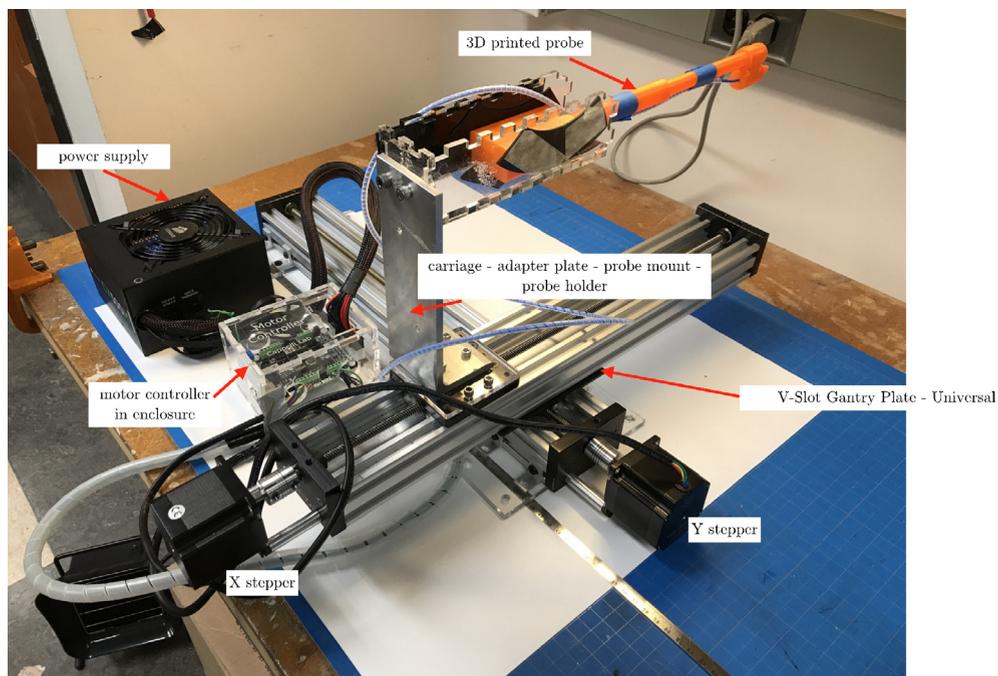
Fig. 1. OpenEM assembled robot with power supply and motor controller enclosure.
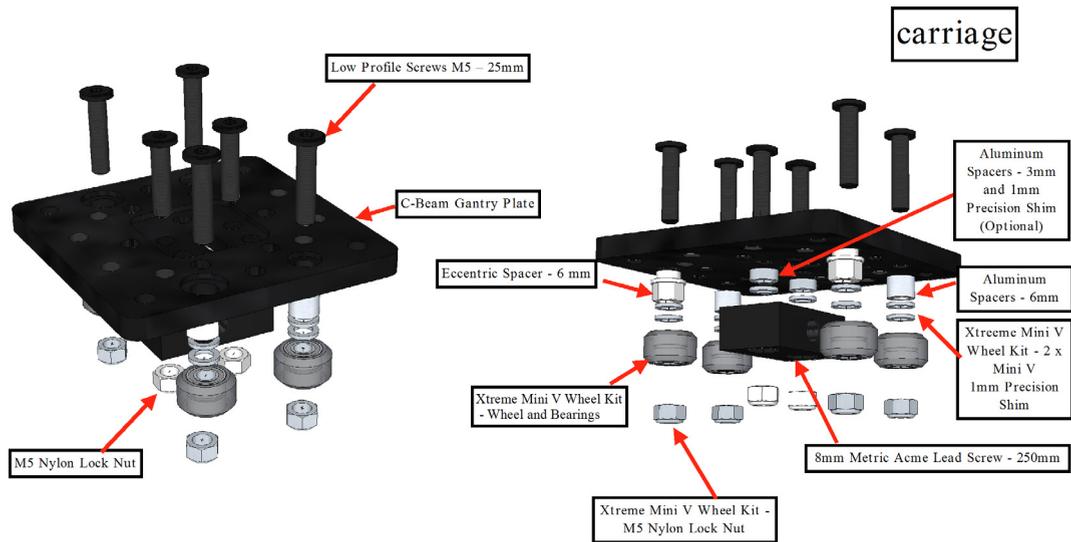
Fig. 2. Carriage assembly diagram for the C Beam Rail.
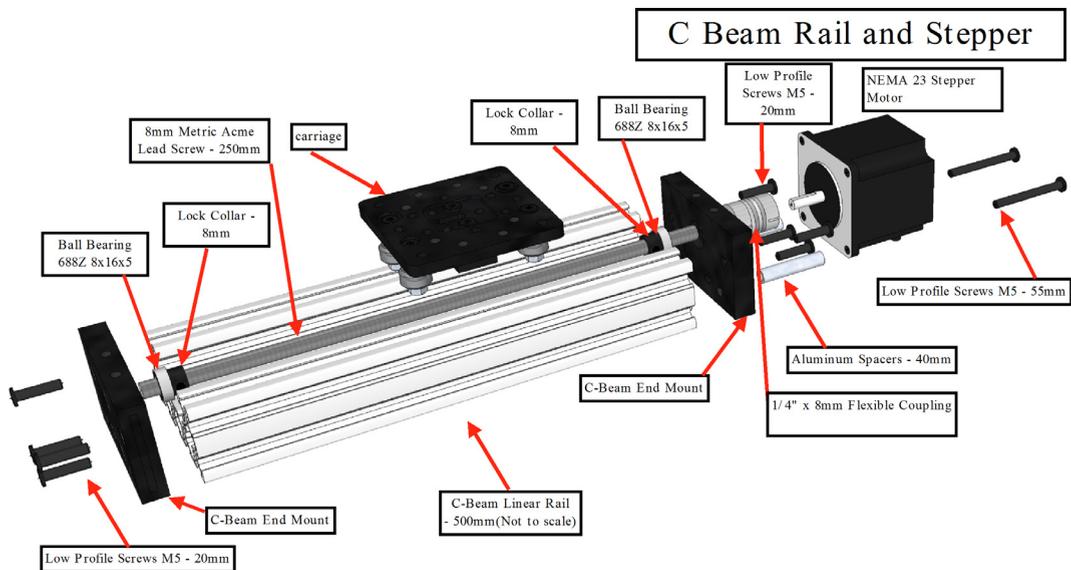
Fig. 3. C Beam Rail and Stepper assembly diagram.

3. Connect the two linear actuators using the Low Profile M5-20 mm screen and the M5 Tee Nuts so that the rails are perpendicular. Slide the 4 M5 Tee Nuts into the bottom of the second rail of the linear actuator that will be on top of the rail setup. Attach the larger Gantry plate to the bottom linear actuator onto the C Beam gantry plate using 4 M5-20 mm screws. Attach the second linear actuator with the T nuts to the larger Gantry plate using the M5-20 mm screws. Fig. 1 shows the correct orientation of both of the linear actuators.

4. The enclosure for the CNC xPro Controller V3 is made using acrylic. ¼ inch acrylic is cut using a laser cutter (Full Spectrum Laser Hobby Series 20 × 12 CO2 5th GEN) and placed into an acrylic enclosure. The laser cut file is included in the current paper (Motor_Box_Final.pdf). The box is designed to be put together with a press fit, but can also be acrylic cemented. Use nylon screws and spacers to mount the circuit board to the bottom of the enclosure.

5. Wire the X and Y stepper motors into the CNC xPRO Controller V3 according to the wiring diagram provided in supplementary materials (CNC xPRO QUICK START GUIDE V2.pdf, https://osf.io/j4qf5/). Attach the computer power supply to the CNC xPro Controller and also the USB cable (see Fig. 4).
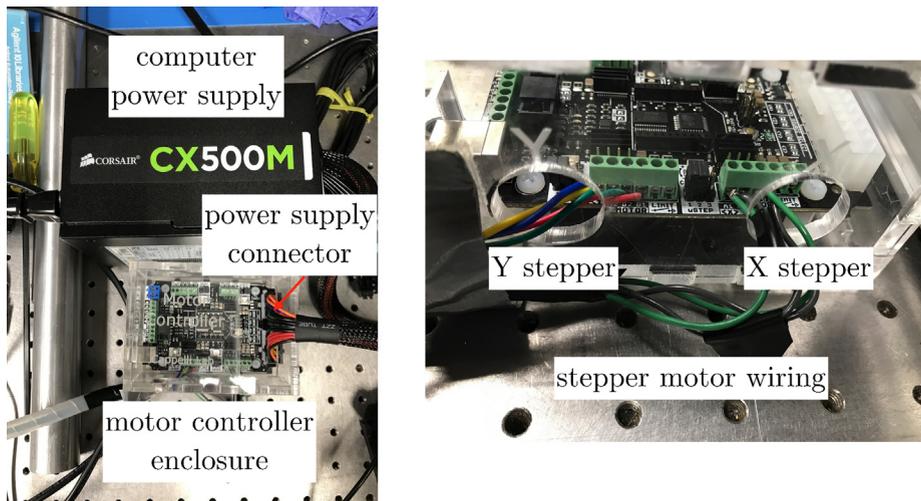
Fig. 4. Left: Computer power supply, power supply connector and motor enclosure. Right: Y stepper and X stepper wiring into motor controller enclosure.

6. EM probe

The EM probe consists of a 3D printed microwave probe and a modified SMA cable with an exposed conductor tip acting as a monopole antenna. PLA (Polyactic acid) is a commonly used material for 3D printing and can be used to make extremely thin and strong shelled structures. The dielectric properties of PLA [7] have been measured to have a permittivity between 2.5 and 3.5 depending on the manufacture and 3D printing settings, and also have a loss tangent on the order of 0.001 [5,6] for 2–10 GHz frequencies. This makes it a very useful material because of its low loss and absorption, and also the ability to make extremely thin (0.2 mm or less) shells that do not interact much with the microwaves.

1. A FlashForge Pro 2016 3D Printer was used to print out the microwave probe components. PLA (Polylactic acid) was used as the printing material because of its relative low absorption and reflection in the 2–18 GHz frequency range. The probe head was designed to stabilize the SMA cable and exposed center male pin that acts as a monopole antenna. Fig. 5 shows the probe with the SMA pin in the probe head.
2. The probe consists of four 3D printed parts that are connected by press fitting each component. The four STL parts are shown in Fig. 6. Simplify3D V.4.0 was used as the software for printing the probe. All 3D printing software settings are located in the supplementary material (https://osf.io/qahtp/) with the infill set to minimize interference with RF waves.
3. The SMA cable needs to be modified in order to be used as the probe antenna. One of the SMA male connectors needs to be carefully removed while keeping the center conductor pin intact with the rest of the cable. A single blade razor can be used to cut through the insulation and the SMA head can be pulled off. The floating coupling unit with the SMA head must be removed manually and the inner pin exposed and connected to the solid center conductor. Fig. 7 shows a diagram of the SMA cable and how to fabricate the monopole antenna correctly. This is very important and must be carefully done in order for the antenna to function properly.
4. Use 3M blue painters tape to attach the SMA cable to the 3D printed probe. See figure on location on probe to connect SMA cable. The connection points are at the center of each of the small and large poles for the probe.
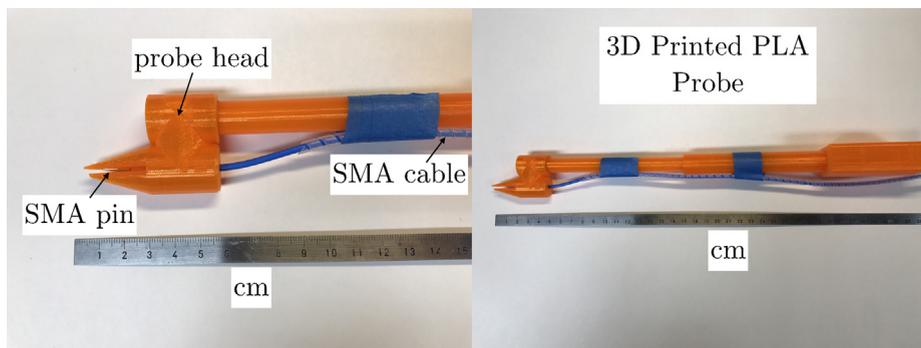
Fig. 5. Left: 3D Printed Microwave Probe head with SMA pin and cable. Right: Assembled 3D printed PLA microwave probe with all 4 printed components.
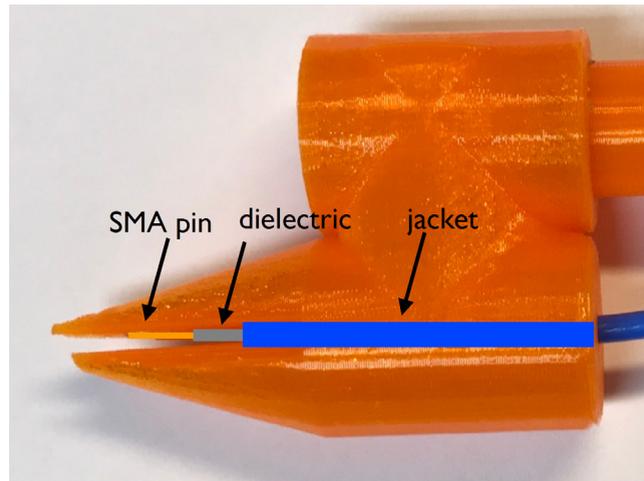
Fig. 6. Zoomed in Microwave probe head with diagram of SMA cable inserted into head. Note the exposed SMA pin acts as the monopole antenna and is a press fit between sides of the probe head.
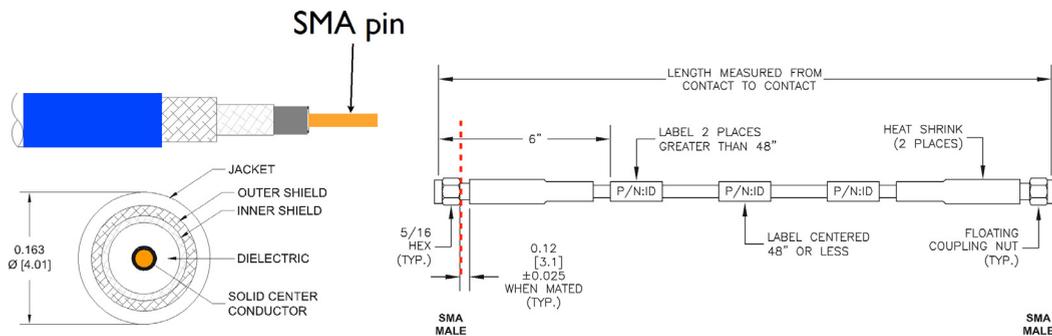
Use X-acto knife and cut outer jacket, outer shield and inner shield at red dotted line and remove floating coupling nut.
Make sure the SMA pin is exposed and attached to inner conductor.

Fig. 7. Diagram on the SMA cable and how to create monopole antenna from SMA cable.

7. Probe stand assembly

1. The probe stand consists of an acrylic adapter plate (Fig. 7), an aluminum L bracket (Fig. 8), and an acrylic probe mount (Fig. 9). This probe stand assembly is specifically built dimensionally for a particular use case and can be modified for use in different experimental setups.
2. The carriage mount is a square piece of acrylic that is laser cut with holes to allow the L bracket to be attached. Additionally, it can be fabricated with an end mill and drill press.
3. The aluminum L bracket (Fig. 8) is machined from ¼" thick aluminum. Additionally, it can be 3D printed with the included STL file (probe_stand.stl), with 100 percent infill.
4. The probe mount (Fig. 11) was fabricated using acrylic and a laser cutter (Full Spectrum Laser Hobby Series 20 × 12 CO2 5th GEN). The probe mount is a four-panel rectangular enclosure (12 in. by 3 in. by 3 in.) with Resistant Compressible - Buna-N Gasket cut into approximately 3 in. long pieces and taped in to the sides with double sided tape. This provides a press fit for the 3D printed probe to be inserted, while also providing some vibration reduction and ease of removal. Two holes that are 1 in. apart and also 0.2660" in diameter need to be drilled on the side of the probe mount for attachment of the probe mount to the L bracket. The location can vary depending on the height of the probe but should be near the middle of the bracket.
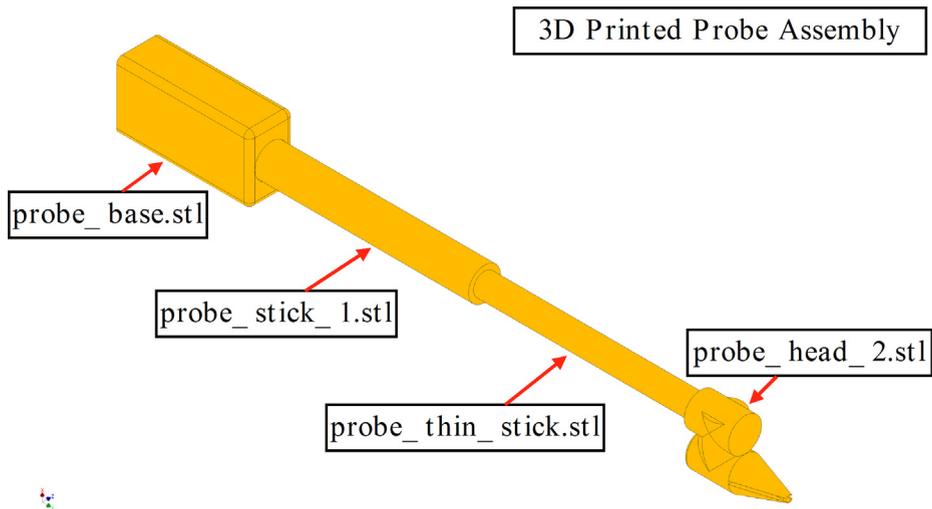
Fig. 8. 3D Printed Probe Assembly consisting of the four 3D printed parts.
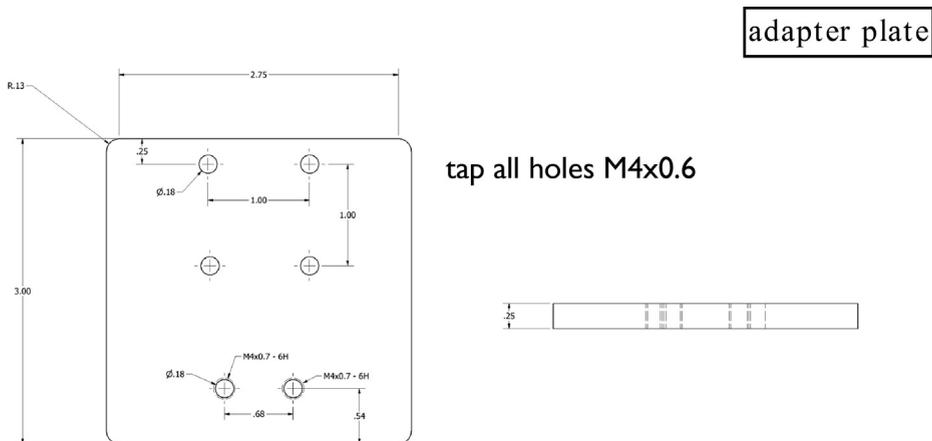
Fig. 9. Adapter plate drawing – This part can be machined out of acrylic or 3D printed.

5. The adapter plate is attached to the top rail carriage with M4 screws. The tapped holes allowed the aluminum L bracket to be attached with M4 screws. The probe mount is attached to the L bracket with ¼"-20 hex screws and nuts (see Figs. 10 and 11).

8. Operation instructions

Complete operating instructions are included in the supplementary material (https://osf.io/5ga4v/).

9. Computer setup

The current instructions are for the included LabVIEW VI controller to automate the data collection process. The computer used is a Lenovo Laptop A6-Series with Windows 10. Due to the way drivers are configured for LabVIEW, the order of all instructions must be followed exactly as specified. The LabVIEW software rasters the stepper motors in a square grid, which can have a resolution up to 0.5 mm. VNA settings are designed to be set independently, including the frequency range, frequency points, and source power level. The current VI only pulls the amplitude and the phase of the VNA at a given location of the robot, which allows for flexibility for any kind of RF measurement. The current calibration allows for a THRU calibration at the further point of the measurement domain aligned with the horn antenna. This allows for a zero phase, normalized amplitude point and for the measured amplitude to be referenced to this point.

The current LabView controller has serial commands that are designed for the HP 8722D VNA. These SCPI commands are standardized and sent through serial commands, and most modern VNAs use some similar kind of method for communica-
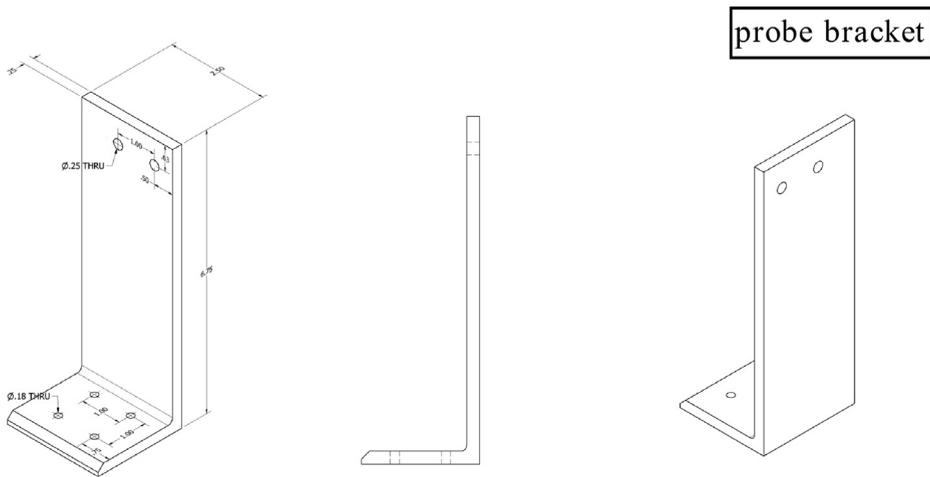
Fig. 10. Probe bracket drawing – This part can be machined out of aluminum or 3D printed.
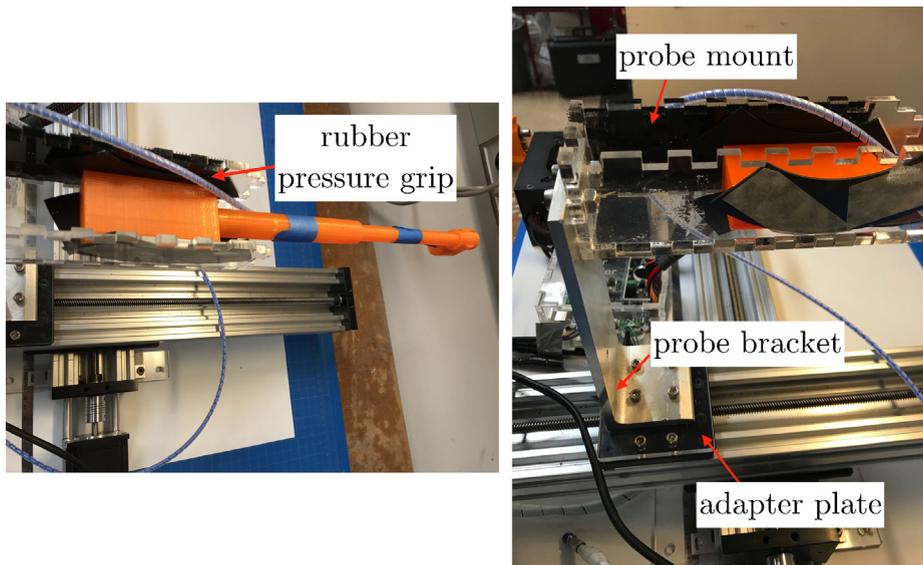
Fig. 11. Left: 3D printed probe mounted to the probe mount using a press fit. The rubber gasket allows a tight pressure-fit with some added vibration dampening. Right: Completed probe mount assembly with probe bracket and adapter plate.

tion and automating the VNAs. The LabView VIs are commented and have places where the commands can be modified for other models of VNAs that do not use SCPI commands.

10. Included LabView VIs

Stepper_move.vi - Separate stepper motor VI to allow manual control of the stepper motors.
OpenEM_VI Directory - All VI must be in same folder/directory.
Home_Stepper.vi - A VI file from the LabVIEW LIFA library that allows the stepper motors to interface with LabVIEW.
OpenEM_Run.vi - The main VI that controls both the VNA and OpenEM steppers.
VNAMeasure.vi - The sub-VI that controls the VNA and allows the VNA data to be saved as text files.

11. Included Python processing Programs

VNA.py - A python script that processes all of the data from the VNA and allows for the generation of field maps. Included is sample experimental results that can be used to generate fields from a horn antenna.
Measurement Equipment:

Vna - HP8722D
Agilent Technologies 82357B USB2.0/GPIB Interface

Software Required:

LabVIEW 2014
NI VISA 14
Keysight IO Libraries Suite 15
LabVIEW LIFA 2.2.0.79 - Must be installed to have proper VIs for use with the other included LabVIEW VIs.
Anaconda Python 2.7 (For Post Data Processing)
Arduino IDE

Completed operating instructions are included in the supplementary material. The order of the steps are extremely important to properly interface the Arduino, GPIB and LabVIEW.

12. Arduino setup and device testing

A modified Arduino LIFA firmware is required in order to operate correctly with the LabVIEW VIs in this system. The modified firmware changes the ports for the Arduino LIFA firmware that controllers the stepper motor functions. The modified firmware is included in the supplementary material (https://osf.io/pbw43/) and should be uploaded to the Stepper Controller. Use the included Stepper_move.vi to test that both stepper motors can be moved using LabVIEW.

13. Validation and characterization

The complete system was validated using field characterization measurement of the fields electromagnetic waves propagating from a microwave horn antenna. In addition, the electromagnetic fields of a propagating electromagnetic wave scattering off a stainless steel (diameter = 3.5 cm) cylinder were also measured. Fig. 12 shows the experimental setup of the OpenEM robot, along with the RF measurement equipment. The measurement domain is a 25 cm (x) by 20 cm (y) square region located 33 cm from the front opening end of the horn antenna, as shown in Fig. 13. The measurement was carried out using an HP 8722D Vector Network Analyzer connected to a A-INFO LB-20180 2-18 GHz Broadband Horn Antenna. In this measurement, a step size of 0.5 cm (1000 stepper units) with (2000 stepper units = 1 cm) is used to measure the amplitude and phase between 2 and 18 GHz with 201 frequency points.

The amplitude and phase are recorded from the OpenEM software and the plotted E field (amplitude*sin(phase)) is shown for the antenna and the antenna scattering off of the metallic cylinder in Fig. 14. The resulting mapped E fields show some very interesting characteristics. The horn itself has a slight curved wavefront that varies with frequencies, with a tighter beam at higher frequencies. The measurement wavefronts provide more information of the actual fields than the provided antenna measurement radiation patterns provided by the manufacture of the horn antennas. The scattering on the metallic rod is also interesting, and has the characteristic wakes located to the left and right behind the metallic rod. In addition, the flattening of the wavefront is shown in the measurement, which is expected for a slightly curved wave front incident on a metallic cylinder.
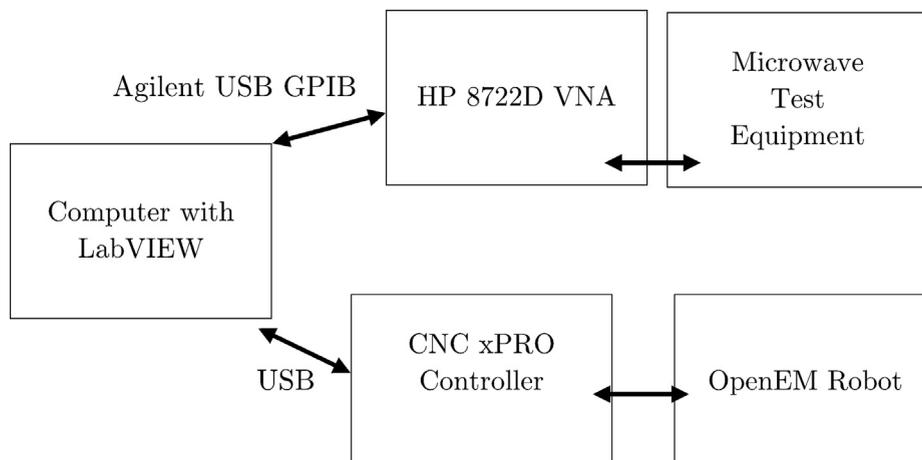
Fig. 12. OpenEM Hardware and Software Block Diagram.
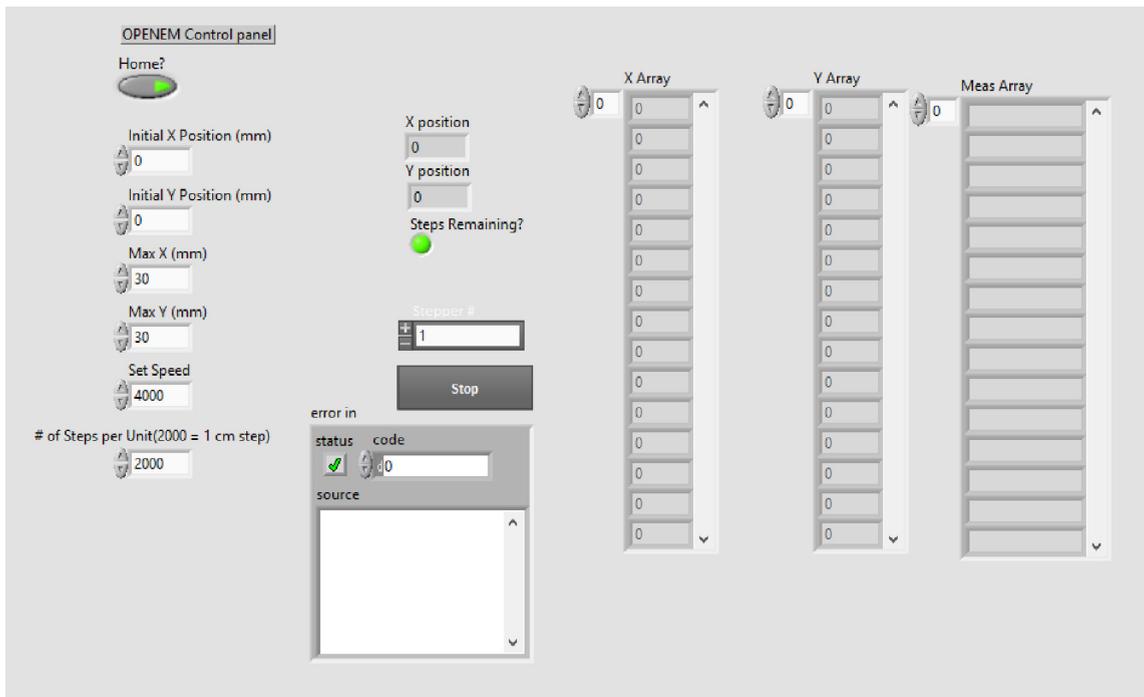
Fig. 13. LabVIEW Controller Interface that syncs that VNA and OpenEM stepper motors and allows the adjustment of the step distance and also measurement domain size.
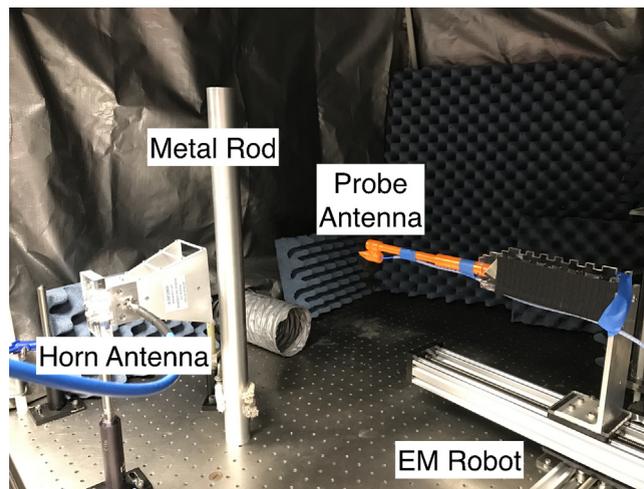
Fig. 14. Experimental setup for measurement of the electromagnetic fields of a 2–18 GHz Horn antenna and the scattering off of a metal rod.

The measurement results for the antenna for all frequencies is provided in the supplementary material (VNA_DATA_CAL_6_12_18.zip, https://osf.io/94beh/) OpenEM outputs a series of data text files that includes the relative coordinates, as well as the amplitude and phase for frequencies set on the VNA. A python program (VNA.py) processes all of the data and plots a map of the electromagnetic field. Characterization of the frequency response of the probe is completed 2–18 GHz, which the probe can successfully resolve both the phase and amplitude as well as reconstructing the wave fronts accurately. The values of the measurements are normalized during the VNA calibration procedure such that the point directly in line with the horn that is furthest away is set to have a normalized amplitude of 1 and a phase of 0 (see Figs. 15 and 16).
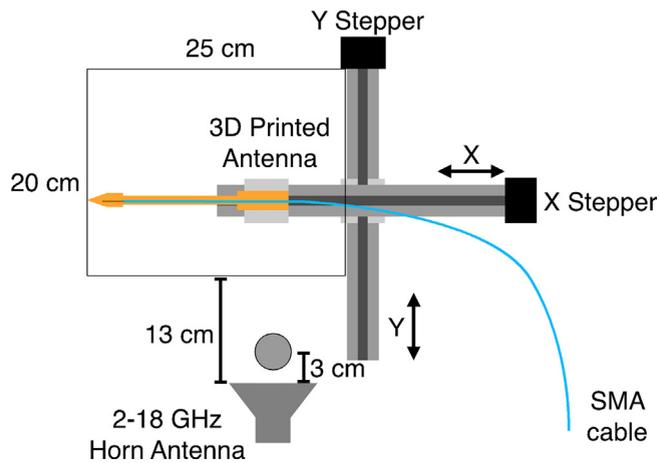
Fig. 15. Diagram for the experimentally setup of measurement of scattering off of a metallic rod.
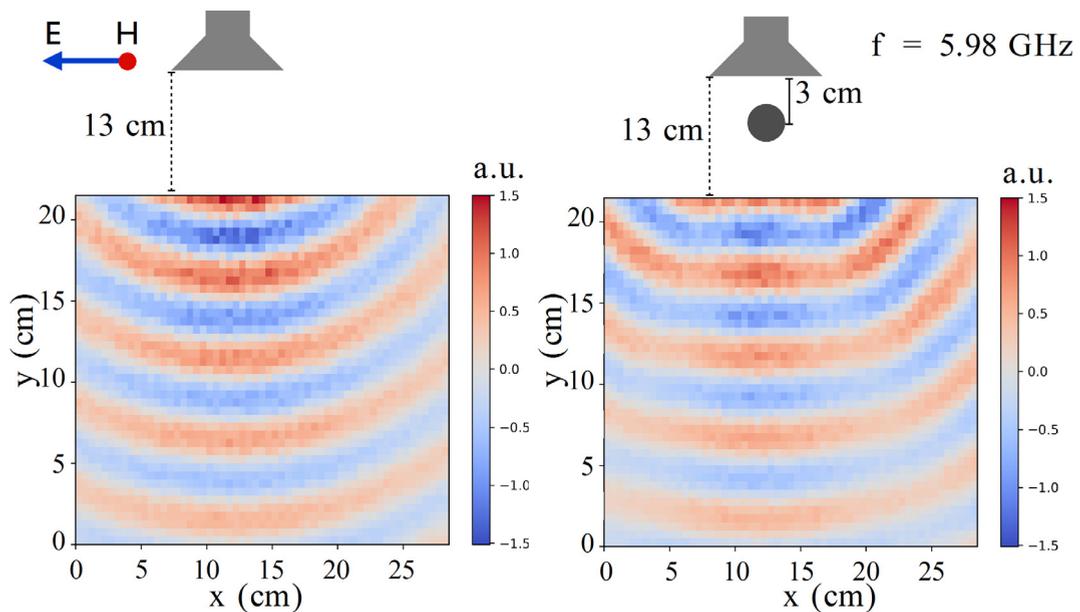
Fig. 16. Electromagnetic field maps (f = 5.98 GHz) of (left) The E field of the horn and (right) the scattered E field from a metal rod with diameter d = 3.5 cm.

14. Conclusion

OpenEM is a low cost, modular, near field measurement system for characterizing electromagnetic fields. This is especially important for characterizing devices such as antennas, microwave photonic crystals, reflectors, metamaterials, and other RF devices. There are also applications in physics education, as the OpenEM robot can be used in courses to visualize electromagnetic waves and be utilized in labs where students can see how EM waves scatter and interact with different materials and devices.

Conflict of interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work. For full disclosure statements refer to https://doi.org/10.1016/j.ohx.2019.e00062.

Acknowledgements

Appendix A. Supplementary data

All supplementary data, programs, and schematics can be found in the OSF repository at http://osf.io/n3dpf/. Supplementary data to this article can be found online at https://doi.org/10.1016/j.ohx.2019.e00062.

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