Description of document: Air Force Office of Scientific Research (AFOSR) technical proposal and grant award document for grant FA8655-10-1-3024, assistance for research entitled: "Metamaterial-Based Cylinders Used for Invisible Cloak Realization," 2009-2010

Request date: 2011

Released date: 15-November-2011

Posted date: 16-March-2015

Source of document: Air Force Office of Scientific Research
875 N. Randolph, Ste.325, Room 3112
Arlington VA, 22203-1768
Fax: (703) 696-5233
Email: publicaffairs@afosr.af.mil

DEPARTMENT OF THE AIR FORCE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFOSR)
875 N. Randolph St Ste 325, Arlington, VA 22203-1768

15 Nov 11

We received your Freedom Information Act (FOIA) request for "a copy of the technical proposal, contract award, final report and presentation slides provided by grantee for grant FA8655-10-1-3024. Attached you will find the following available documents responsive to your request: 1) The technical proposal for grant FA86551013024 and 2) grant award document. Unfortunately, we are responsive documents for presentation slides and the final report is currently not available as well.

There are no fees associated with this request as there was only 1 hour search time and 7 electronic pages.

If you have any further questions, please call Ms Yvonne Mason at 703-696-9518.

Sincerely,

// SIGNED //

YVONNE MASON
FOIA Manager

1 Attachment

Grant/Cooperative Agreement Award

1. AWARD NO.	2. EFFECTIVE DATE	3. PURCHASE REQUEST NO	4. CFDA NO.	PAGE OF
FA8655-10-1-3024	22 JUL 2010	See Block 16	12.800	1 3

5. ISSUE BY EOARD CODE FA8655
EUROPEAN OFFICE OF AEROSPACE RESEARCH AND DEVELOPMENT
UNIT 4515 BOX 14
APO AE 09421 USA
WENDY HARRISON +44(0)18956161
wendy.harrison@london.af.mil

6. AWARDED TO CAGE CODE A01MB
UNIVERSITY OF ZAGREB
FACULTY OF ELECTRICAL ENGINEERING
UNSKA 3
ZAGREB HR-10000 CROATIA

7. AUTHORITY
10 U.S.C. 2358

8. PERIOD OF PERFORMANCE
22 July 2010
To
21 July 2011

9 SCOPE / AGREEMENT TERMS
Assistance is for Research entitled, "Metamaterial-Based Cylinders Used for Invisible Cloak Realization ." The "Air Force Research Laboratory Grants Terms and Conditions Sep 2009 - Awards to International Educational Institutions and Non-Profit Organizations" and the Recipient's Technical Proposal are incorporated by reference. Awardee signature is not required on this agreement; however, the recipient agrees to the conditions specified in this award unless notice of disagreement is furnished to the awarding officer within 15 days after the signature date. In case of disagreement, the recipient shall not incur any costs until the disagreement is resolved.

10. RECIPIENT PRINCIPAL INVESTIGATOR
Professor Zvonimir Sipus

11. OTHER SPONSORING AGENCY(S)
N/A

12. ADMINISTRATIVE OFFICE CODE FA8655
EUROPEAN OFFICE OF AEROSPACE RESEARCH AND DEVELOPMENT
86 BLENHEIM CRESCENT
RUISLIP, MIDDLESEX HA4 7HB
UNITED KINGDOM

13. PAYING OFFICE CODE: F78900
DFAS-LI
27 ARKANSAS ROAD
LIMESTONE MAINE 04751-6216
USA

14. STAFF JUDGE ADVOCATE OFFICE
AFOSR/JA (703) 696-9500
875 NORTH RANDOLPH STREET
SUITE 325, ROOM 3112
ARLINGTON, VIRGINIA 22203 USA

15. GCVT PROGRAM MANAGER (Name, Org, Tel, Email)
Scott Dudley, Lt Col, USAF, +44 (0) 189 561 6162, Scott.Dudley@london.af.mil

16. ALLOCATED FUNDING: The following funds with associated Accounting Classification reference number(s) (ACRNs) are allotted to this agreement:

ACRN **FUND CITATION(s)** **AMOUNT**

SEE CONTINUATION

SPECIAL INSTRUCTIONS: PAYMENT WILL BE MADE BY ELECTRONIC FUNDS TRANSFER.
PAYING OFFICE INSTRUCTIONS: USE EARLIEST CITED FUNDS FIRST.
PAYMENT SCHEDULE (if applicable): SEE FOLLOWING PAGE(S) FOR REPORT AND PAYMENT SCHEDULE AND INSTRUCTIONS

	Government Share	Recipient Share	Total	
17. TOTAL FUNDS OBLIGATED	$30,000.00	$0.00	$30,000.00	18. INVOICE INSTRUCTION: INVOICES NOT REQUIRED - SEE FOLLOWING PAGE(S)
19. AMOUNT OF AWARD	$30,000.00	$0.00	$30,000.00	
20. OPTIONS N/A				21. PERIOD

FOR THE RECIPIENT		FOR THE UNITED STATES OF AMERICA	
22. SIGNATURE		23. SIGNATURE Wendy Harrison	
24. NAME AND TITLE	25. DATE SIGNED	26. NAME AND TITLE WENDY HARRISON GRANTS OFFICER	27. DATE SIGNED 22 Jul 10

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Created 22 Jul 2010 3:03 PM

ALLOCATED FUNDING

ACRN	FUND CITATION	AMOUNT
AA	57 03600 290 47DP 614113 6TR0ER 58800 61102F 678900 F78900 PR/MIPR: F3BB000137A714 $15,000.00 Descriptive Data: ALD: AA FSR: 000985 PSR: 030387 DSR: 006443	$15,000.00
AB	57 03600 290 47B3 624916 6TRYHA 559ZZ 62204F 503000 F03000 PR/MIPR: F2BBAW0060H001 $15,000.00 JON: 4916HAMM ESP: MM Descriptive Data: CSN: J0H044 FSR: 006314 PSR: 150817 DSR: 136332	$15,000.00

This grant is funded with basic research appropriations, 6.1 funding and, as such, is subject to limits on F&A and indirect costs as included in the current Appropriation Act. This limit is applicable to awards made on or after 14 Nov 2007. Unless this grant is modified to reflect otherwise, funds obligated under this grant may not be used for payment of F&A or indirect costs in excess of 35% of the total amount of funds obligated on or after 14 Nov 2007.

"Total costs", "F&A costs" and "Indirect costs", for purposes of this clause are defined in 2 CFR 220 (OMB Circular A-21) for Educational Institutions.

Please cite the grant number on all correspondence.

ACKOWLEDGEMENT OF SPONSORSHIP

The Grantee is responsible for assuring that an acknowledgement of Government support will appear in any publication of any material based on or developed under this project, in the following terms: "Effort sponsored by the Air Force Office of Scientific Research, Air Force Material Command, USAF, under grant number FA8655-10-1-3024. The U.S Government is authorized to reproduce and distribute reprints for Governmental purpose notwithstanding any copyright notation thereon."

REPORTS

Article 3. Payment, Article 18 Performance Reports, paragraphs (b) and (c), and Article 19. Financial Reports of the "Air Force Research Laboratory Grants Terms and Conditions Sep 2009 - Awards to International Educational Institutions and Non-Profit Organizations" <http://www.wpafb.af.mil/shared/media/document/AFD-090916-037.pdf> are replaced by the following reporting requirements.

Grantee shall submit performance reports to the Government Program Manager listed in block 15 on page 1 of the Grant Award. Reports should be submitted in English with the following required sections:

Table of Contents
List of Figures (If more than five figures and tables)
List of Tables (If more than five tables and figures)
Summary
Introduction
Methods, Assumptions, and Procedures
Results and Discussion
Conclusions
References

List of Symbols, Abbreviations, and Acronyms

Upon receipt and acceptance of deliverables EOARD will submit an SF270 to DFAS for payment.

ITEM 0001 $30,000.00
Advance Payment.

ITEM 000X $0.00 (NOT TO EXCEED)
Payment will be made after receipt and acceptance of a comprehensive final report, a completed DD 882, "Report of Inventions and Subcontracts (Pursuant to "Patent Rights" Contract Clause)," and a completed Federal Financial Report (SF 425) due no later than 12 months after start of period of performance stated in block 8 of grant award document. Electronic copies must be in either .doc, .rtf, or .pdf, format and must be submitted as a single file (an email attachment is acceptable).

SPC ON LINE SUBMISSION DETAILS

Date Submitted	23-Sep-09
Name:	Professor Zvonimir Sipus
Organization:	Unversity of Zagreb
Branch:	Faculty of Electrical Engineering and Computing, Department of Wireless Communications
Address:	Unska 3
City:	Zagreb
Region:	
Post Code:	HR-10000
Country	Croatia
Work Phone:	+385 1 61 29 798
Home Phone:	[redacted] (b6)
Fax:	+385 1 6129 717
Email:	zvonimir.sipus@fer.hr
URL:	www.rc.fer.hr/en/zsipus

SPC Title:	Metamaterial-Based Cylinders Used for Invisible Cloak Realization
Start Date:	11-Jan-09 (estimated)
Duration:	12 months

Abstract

Uniaxial cylindrical cloaks have recently been proposed to prevent scattering of electromagnetic waves, i.e. to render objects invisible. The proposed cloaks with reduced variation of constitutive parameters suffer from nonzero reflectance, i.e. they are only partly invisible. Therefore, we propose a 12-month effort to develop an analysis method and the corresponding software for analyzing cylinders made from metamaterial-based concentric layers with an application to invisible cloak realization. The main parameter of interest is the scattered field, i.e. if the considered structure really appears invisible to the incident wave. The considered structure will be modeled as a multilayer anisotropic cylinder where both permittivity and permeability tensors are diagonal in the cylindrical coordinate system. The active cloaks can be also analyzed in this way since their homogeneous electromagnetic model is based on complex constitutive parameters. The proposed analysis method includes transient analysis, i.e. by this it is possible to determine response to the pulse excitation (for example, response to the radar signal). The proposed analysis method will be connected with a suitable global optimization routine, and the developed software package will be used to design an experimental prototype. A possible application of the considered prototype is reduction of scattered field from mechanical structures that need to be placed in front of big antennas, such as radar antennas or reflector systems.

SOW

1. PROBLEM IDENTIFICATION AND ITS SIGNIFICANCE

The realization of structures that do not scatter electromagnetic field, i.e. structures that appear invisible for EM waves is not a new concept. The possibility of a plane wave passing through some structure without distortions (i.e. with zero scattered field) has been investigated theoretically since 1960s (see e.g. [1]-[4]). Recently, the possibility of cloaking objects using a metamaterial cover has extensively been studied ([5]-[7]). In this approach, material has been used to render a volume effectively invisible to incident radiation, i.e. to squeeze space from a volume into a shell surrounding the concealment volume. Coordinate transformations that are used for cloak design do not influence the form of Maxwell's equations, but they affect permittivity and permeability tensors (ε and μ, respectively), making the needed materials spatially varying and anisotropic. When viewed externally, the concealed volume and the cloak both appear to have the propagation properties of free space, i.e. they appear invisible to electromagnetic waves. The required anisotropy is supposed to be obtained by using metamaterials.

As a sort of canonical case, cloaking of the PEC cylinder has been considered. For the cloak design, a coordinate transformation which compresses free space from the cylindrical region 0 < r < b into the concentric cylindrical shell a < r' < b is applied, where a and b represent the cloak inner and outer radius, respectively. After using the coordinate transformation [5] it can be shown that all the components of permittivity and permeability tensors are functions of radius, which implies a very complicated metamaterial design.

However, in [6], a simplified metamaterial cloak design is proposed for case of fabrication, which is intended to work properly at microwave frequencies when illuminated with a normal incident plane wave with the electric field polarized along z-axis (TMz cloak). This cloak is referred in this proposal as Schurig cloak. Such case benefits from a substantial simplification due to more flexibility in choosing the functional forms for the electromagnetic material parameters: it is possible to let only the radial component of permeability to vary along the radial direction, and to fix all other components of permeability and permittivity tensors.

Note that the required radial anisotropies could be realized by using layers of metamaterials, in particular split ring resonators for the TMz cloak. In [7] dual case (TEz cloak) was proposed which could be realized by using metal wires embedded in a dielectric material. Therefore, such simplified cloaks are possible to be realized, and are of interest to further analysis and improvement.
In [8] these structures have been analyzed in order to quantify the achieved invisibility in mathematical terms. The analysis approach is based on the modal approach, i.e. the radial field distribution is described with a modified Bessel differential equation that takes into account the radial anisotropy of the proposed structures. The invisibility is characterized in terms of total scattering width (σT) of the cloaked cylinder and the angular variation of bistatic scattering width (σ2D) [9]. Furthermore, the total scattering width for PEC cylinder without cloak has been calculated as the referent case, which enables comparing different cloak realizations.

The radial anisotropy of μr or εr has been approximated by piecewise constant functions representing the stepwise cloak realization (layers of metamaterial), and for all the analyzed structures it has been shown that there is no significant improvement of the obtained invisibility gain for structures with more than 5 layers of metamaterial [8]. Furthermore, it was shown that the obtained invisibility gain of the Schurig cloak is only around factor 3 [8]. The main reason for such small gain is the reflection of the incident wave from the cloak surface ([6], [7]), due to the impedance mismatch.

The bandwidth of simplified cloak realizations has also been considered. In reality, the magnetic permeability in metamaterials is always frequency dependent and is described by the Lorentz model [10]. Thus the frequency variations of μr have also an effect on the level of the achieved invisibility. It is shown that the invisibility bandwidth (relative frequency range where the invisibility gain is larger than 1) is only around 0.2% for the Schurig cloak [8].

Previous work in invisibility, therefore, gives rise to several questions:
1. Is it possible to realize a cloak with the reduced set of material properties that is entirely invisible (at least at the central frequency)?
2. Is it possible to enlarge the bandwidth of such a cloak?
3. Is it possible to realize a cloak with the reduced set of material properties that work for oblique direction of incident wave?
4. Is it possible to realize a cloak that is invisible to pulse excitation (i.e.to radar)?
The purpose of the project is, therefore, to provide further analysis of this issue.

The possible application of the developed cloak will be reduction of the scattered field from some mechanical structure. In more details, there are many situations where electromagnetic waves are obstructed by some mechanical structure. The obstruction may represent aperture blockage causing increased sidelobes and reduced gain, if the structure is a part of the antenna system or if it is placed close to the antenna,. Examples of such structures are objects placed in the vicinity of the antenna system (e.g. musts on ships near radars or communication systems), supporting struts in large reflector systems, etc. In all such systems the frequency, polarization and angle of incidence are known which make possible to construct a special structure that will reduce the scattered field.

2. WORK PLAN

The work in the project will be divided in the following tasks:

1. Extension of the program for analyzing uniaxial multilayer cylinders – with the extended version it will be possible to analyze the case when the incident field has oblique direction of propagation and oblique polarization.

2. Merging of the program for analyzing uniaxial cylindrical structures with the global optimization program. As a global optimization algorithm we have chosen the Particle Swarm Optimization (PSO) algorithm. This is an evolutionary algorithm similar to the genetic algorithm and to the simulated annealing, but it operates on a model of social interactions between independent agents and utilizes swarm intelligence to achieve the goal of optimization problems. It was chosen here since the associated algorithm has the same or better performances comparing to other global optimization programs. [11, 12].

3. Extension of the program in order to include the transient analysis of the structure. One of the goals of the cloak investigation is to make the cloaks invisible to radar signals. In order to design such a cloak it is not enough the perform time-harmonic analysis, i.e. the response of the structure to the pulse excitation should be also determined and taken into account in the design procedure.

4. Extension of the program to include cloaks with active components. Active cloaks can be electromagnetically modeled using asymptotic homogenized material parameters, and the gain inside such a structure can be taken into account if the structure is described with complex unisotropic permittivity and permeability tensors.

5. Making a proposal for building an experimental model of a cloak. The goal is to develop the experimental model that is relatively simply to build, and that is invisible for arbitrary-polarized electromagnetic waves in a large frequency bandwidth. The selection of the propsed type of structure will be based on the results of the performed analysis. The proposed model will be a prototype of the structure that reduces scattered field if some mechanical supporting structure needs to be placed in front of the antenna.

3. POSSIBLE CONTINUATION OF THE PROJECT

Proposed one-year effort should give the answer to the question which type of cylindrical structure is suitable for building cylindrical cloaks. In particular, the selected structure should excite low scattered field in the case of arbitrary-polarized incident wave with oblique incoming direction. The bandwidth of the proposed structure will be one of the main parameters. Therefore, in order to fully prove the proposed concept we suggest the following continuation of the project:

• Second year : Designing a prototype of the cloak. In order to be able to make such a design, a detailed analysis of the proposed structure is needed. This is not a simple task since the proposed structure is very large in terms of the wavelength. Therefore, we will combine the commercial electromagnetic solvers (e.g. CST Microwave Studio), the in-hose developed software for analyzing anisotropic cylindrical structures (where it is not possible to design all the details of the structure), and the optimization algorithm.

• Third year: Development and measurements of the experimental cloak model. The developed model will be initially tested at University of Zagreb, but the proper verification should be done at a good-quality anechoic chamber like the one at the Hanscom AFB.

4. TIME LINE - SCHEDULE

The milestones for the project are:
(a) after 3 months: the detailed formulation of the proposed analysis method,
(b) after 6 months: the first version of the program for calculating scattering of general anisotropic multilayered cylindrical structures when the incident field has oblique direction of propagation and oblique polarization,
(c) after 8 months: the first version of the program for transient analysis,
(d) after 9 months: the optimization module that will enable designing an experimental model of a cloak,
(e) after 11 months: the proposal of experimental model,
(f) after 12 months: the final report.

5. DELIVERABLES

The duration of the effort will be 12 months. After 12 months we will deliver:

(a) Program that analyzes anisotropic multilayer cylindrical structures.

(b) Report with the detailed analyis results and with the description of the proposed experimental model (part of the final report).

(b) Program manual with several test runs (part of the final report).
In program manual the detailed description of the analysis method and of the program structure will be given. Several test examples will assure that the program will be used in a proper way.

6 REFERENCES

[1] L. S. Dollin,

Cost Proposal

1. Equipment to be purchased:
   - Two PCs..................................$ 3,100
2. Publications and reports......................$ 500
3. Labor
   - One year three investigators 30% time engagement
     .... $15,000
   - One year principal investigator with 20%engagement
     ....$ 6,000
4. Overhead charges
   - University overhead of 18%..................$ 5,400

TOTAL ESTIMATED COST............................$ 30,000

Total Cost: **$ 30,000**

Check Details

Name/Organization:	Faculty of Electrical Engineering and Computing, University of Zagreb
Address:	Unska 3
City:	Zagreb
State/Province	
Post Code	HR-10000
Country	Croatia