

Stefan Maier

**Guiding of electromagnetic energy in
subwavelength periodic metal structures**

Doctoral Thesis / Dissertation

Bibliographic information published by the German National Library:

The German National Library lists this publication in the National Bibliography; detailed bibliographic data are available on the Internet at <http://dnb.dnb.de> .

This book is copyright material and must not be copied, reproduced, transferred, distributed, leased, licensed or publicly performed or used in any way except as specifically permitted in writing by the publishers, as allowed under the terms and conditions under which it was purchased or as strictly permitted by applicable copyright law. Any unauthorized distribution or use of this text may be a direct infringement of the author s and publisher s rights and those responsible may be liable in law accordingly.

Copyright © 2003 Diplomica Verlag GmbH
ISBN: 9783832466299

Stefan Maier

**Guiding of electromagnetic energy in subwavelength
periodic metal structures**

Stefan Maier

Guiding of electromagnetic energy in subwavelength periodic metal structures

Dissertation / Doktorarbeit
an dem California Institute of Technology (Caltech)
Januar 2003 Abgabe



Diplomica GmbH ———
Hermannstal 119k ———
22119 Hamburg ———

Fon: 040 / 655 99 20 ———
Fax: 040 / 655 99 222 ———

agentur@diplom.de ———
www.diplom.de ———

ID 6629

Maier, Stefan: Guiding of electromagnetic energy in subwavelength periodic metal structures

Hamburg: Diplomica GmbH, 2003

Zugl.: Pasadena, Dissertation / Doktorarbeit, 2003

Dieses Werk ist urheberrechtlich geschützt. Die dadurch begründeten Rechte, insbesondere die der Übersetzung, des Nachdrucks, des Vortrags, der Entnahme von Abbildungen und Tabellen, der Funksendung, der Mikroverfilmung oder der Vervielfältigung auf anderen Wegen und der Speicherung in Datenverarbeitungsanlagen, bleiben, auch bei nur auszugsweiser Verwertung, vorbehalten. Eine Vervielfältigung dieses Werkes oder von Teilen dieses Werkes ist auch im Einzelfall nur in den Grenzen der gesetzlichen Bestimmungen des Urheberrechtsgesetzes der Bundesrepublik Deutschland in der jeweils geltenden Fassung zulässig. Sie ist grundsätzlich vergütungspflichtig. Zuwiderhandlungen unterliegen den Strafbestimmungen des Urheberrechtes.

Die Wiedergabe von Gebrauchsnamen, Handelsnamen, Warenbezeichnungen usw. in diesem Werk berechtigt auch ohne besondere Kennzeichnung nicht zu der Annahme, dass solche Namen im Sinne der Warenzeichen- und Markenschutz-Gesetzgebung als frei zu betrachten wären und daher von jedermann benutzt werden dürften.

Die Informationen in diesem Werk wurden mit Sorgfalt erarbeitet. Dennoch können Fehler nicht vollständig ausgeschlossen werden, und die Diplomarbeiten Agentur, die Autoren oder Übersetzer übernehmen keine juristische Verantwortung oder irgendeine Haftung für evtl. verbliebene fehlerhafte Angaben und deren Folgen.

Diplomica GmbH

<http://www.diplom.de>, Hamburg 2003

Printed in Germany

Acknowledgements

It is my great pleasure to thank the many people that have supported me during my thesis work at Caltech and beyond.

Most of all, thanks is due to my advisor Harry Atwater, whose belief in the success of this project never faltered during the last three years. I cannot recall a single day when he was not willing to discuss obstacles and progress associated with my research, and his constant support and encouragements have been exemplary.

Mark Brongersma deserves most credits for allowing a smooth transition from course work into active research. During his postdoctoral work in our group, he started out the initial investigations into the properties of ordered metal nanoparticle chains, and was of great help in the planning of the first experiments. Most of the knowledge and skills I acquired during this project I owe to him. The void he left after his far-too-early disappearance to Stanford was filled by Pieter Kik, who has supported my research ever since. Pieter's often intuitive insight into physical processes and his strong background in optical experiments were of great help with this thesis.

I also had the great pleasure to work with a number of enthusiastic collaborators outside of Caltech. Thanks to Sheffer Meltzer of the University of Southern California for his willingness to contribute to this project with his invaluable experience as a surface chemist. He assembled a great number of nanoparticle structures using his dedicated atomic force micromanipulation system. During the last months of this work, Elad Harel of the University of California in San Diego continued in Sheffer's footsteps.

For me, it was always a daunting task to conduct experiments whose success or failure depend on the ordered arrangement of nanoscale structures and thus heavily on the

quality of the samples. But as it turned out there was no reason for worry since I was working with the very best - Richard Muller, Paul Maker and Pierre Echternach of the Jet Propulsion Laboratory in Pasadena. Thanks to them for their invaluable help with electron beam lithography.

The experimental part of this work has benefited a lot from discussions about near-field optical microscopy with Aaron Lewis of Nanonics Imaging Ltd. in Jerusalem. I am very grateful for his aid in setting up a reliable and intricate near-field microscopy station.

Funding for this work was mainly provided by the National Science Foundation through the Center of the Science and Engineering of Materials at Caltech and the Air Force Office of Scientific Research.

During my stay in Harry's group I was lucky to be surrounded by a number of great fellow students. I especially want to thank Luke Sweatlock for a lot of good and fun discussions and Robb Walters for providing a great office atmosphere.

I would never have had the pleasure of meeting all these fine people had it not been for two advisors that especially influenced me during my studies at Technische Universität München. Thanks to Fred Koch and Dmitri Kovalev for their training and encouragement, and for the great times in the beer gardens.

And of course, nothing would have been and is possible without Mag.

Abstract

The miniaturization of optical devices to spatial dimensions akin to their electronic device counterparts requires structures that guide electromagnetic energy with a lateral confinement below the diffraction limit of light. This cannot be achieved using conventional optical waveguides or photonic crystal defect waveguides. Thus, a size mismatch between electronic and optical integrated devices exists and needs to be overcome.

In this thesis, the possibility of employing plasmon-polariton excitations in “plasmon waveguides” consisting of closely spaced metal nanoclusters with a subwavelength cross section for the confinement and guiding of electromagnetic energy is examined both theoretically and experimentally. The feasibility of energy transport with mode sizes below the diffraction limit of visible light over distances of several hundred nanometers is demonstrated.

As a macroscopic analogue to nanoscale plasmon waveguides, the transport of electromagnetic energy in the microwave regime of the electromagnetic spectrum along structures consisting of closely spaced centimeter-scale metal rods is investigated. The dispersion relation for the propagation of electromagnetic waves is determined using full-field electrodynamic simulations, showing that information transport occurs at a group velocity of $0.65c$ for fabricated structures consisting of centimeter-scale copper rods excited at 8 GHz ($\lambda = 3.7$ cm). The electromagnetic energy is highly confined to the arrays, and the propagation loss in a straight array is about 6 dB/16 cm. Routing of energy around 90-degree corners is possible with a power loss of 3-4 dB, and tee structures for the splitting of the energy flow and for the fabrication of an all-optical

modulator are investigated. Analogies to plasmon waveguides consisting of arrays of nanometer-size metal clusters are discussed.

The possibility of guiding electromagnetic energy at visible frequencies with mode sizes below the diffraction limit is analyzed using an analytical point-dipole model for energy transfer in ordered one-dimensional arrays of closely spaced metal nanoparticles. It is shown that such arrays can work as plasmon waveguides that guide electromagnetic energy on the nanoscale. Energy transport in these arrays occurs via near-field coupling between metal nanoparticles, which sets up plasmon modes. This coupling leads to coherent propagation of energy with group velocities exceeding the saturation velocity of electrons in semiconductor devices. The point-dipole model suggests the feasibility of complex guiding geometries such as 90-degree corners and tee structures for the routing of electromagnetic energy akin to the fabricated macroscopic guiding structures, and the possibility of an all-optical modulator operating below the diffraction limit is suggested.

The interparticle coupling in plasmon waveguides is examined using finite-difference time-domain (FDTD) simulations. Local excitations of plasmon waveguides show direct evidence for optical pulse propagation below the diffraction limit of light with group velocities up to $0.06c$ in plasmon waveguides consisting of arrays of spherical noble metal nanoparticles in air. The calculated dispersion relation and group velocities correlate well with predications from the simple point-dipole model. A change in particle shape to spheroidal particles shows up to a threefold increase in group velocity for structures that can be fabricated using electron beam lithography. Pulses with transverse polarization are shown to propagate with negative phase velocities antiparallel to the energy flow.

Plasmon waveguides consisting of spherical and spheroidal gold and silver nanoparticles were fabricated using electron beam lithography with lift-off on ITO coated quartz slides. Far-field polarization spectroscopy reveals the existence of longitudinal and transverse collective plasmon-polariton modes. Measurements of the polarization dependent extinction confirm that the collective modes arise from near-field optical interactions. The key parameters that govern the energy transport are determined for various interparticle spacings and particle chain lengths using measurements of the resonance frequencies of the collective plasmon modes. For spherical Au nanoparticles with a diameter of 50 nm and an interparticle spacing of 75 nm, the energy attenuation of the plasmon waveguide is 6 dB/30 nm. This loss can be reduced and the energy attenuation length conversely increased by approximately one order of magnitude by using spheroidal silver nanoparticles as building blocks of plasmon waveguides, which show an enhanced interparticle coupling and a decreased plasmon damping.

Near-field optical microscopy allows for the local optical analysis and excitation of plasmon waveguides. Using the tip of a near-field optical microscope as a local excitation source and fluorescent polystyrene nanospheres as detectors, experimental evidence for energy transport over a distance of about 0.5 μm is presented for plasmon waveguides consisting of silver rods with a 3:1 aspect ratio and a center-to-center spacing of 80 nm. Ways to further improve the efficiency of energy guiding in plasmon waveguides and possible applications are discussed.

Table of Contents

Chapter 1 Introduction	1
1.1 Towards nanoscale optical devices	1
1.2 Surface plasmons as a way to overcome the diffraction limit	2
1.3 Road map through this thesis	5
Chapter 2 Yagi waveguides	8
2.1 Introduction.....	8
2.2 The dispersion of a Yagi waveguide	9
2.3 Guiding along linear and corner Yagi arrays: Experiments and simulations....	14
2.4 Towards active devices: A three-terminal modulator	19
2.5 The link to nanoscale plasmon waveguides	22
2.6 Conclusions and outlook	23
Chapter 3 Going nanoscale: Point-dipole theory of plasmon waveguides	25
3.1 Plasmon resonances in small metal clusters	25
3.2 Near-field particle interactions in plasmon waveguides.....	32
3.3 Routing and switching of electromagnetic energy in plasmon waveguides	37
3.4 Conclusions and limitations of the dipole model	39
Chapter 4 FDTD simulations of plasmon waveguides	41
4.1 Introduction.....	41
4.2 Collective far-field excitation of plasmon waveguides	41
4.3 Locally excited plasmon waveguides	49
4.4 Tailoring of the guiding properties by particle design.....	55
4.5 Conclusions and outlook	57

Chapter 5 Fabrication and far-field properties of plasmon waveguides	62
5.1 Introduction.....	62
5.2 Fabrication of plasmon waveguides	63
5.3 Far-field characterization of interparticle coupling in plasmon waveguides	67
5.4 Conclusion and outlook: Decrease of waveguide loss by particle design.....	75
Chapter 6 Local excitation of plasmon waveguides	79
6.1 Introduction.....	79
6.2 Transmission NSOM analysis of plasmon waveguides: Facts and artifacts.....	83
6.3 Molecular fluorescence as a probe for localized electromagnetic fields	89
6.4 Local excitation and detection of energy transport in plasmon waveguides.....	96
6.5 Conclusions and outlook	103
Chapter 7 Conclusions and outlook	109
Bibliography	116

Table of Figures

Figure 1-1 (color): Optical fibers and photonic crystals.....	1
Figure 1-2 (color): Sketch of a plasmon waveguide network coupling two conventional dielectric plane waveguides	5
Figure 1-3 (color): Artist's rendition of a plasmon waveguide	7
Figure 2-1 (color): Yagi antennas	8
Figure 2-2 (color): Geometry of a short 10-element Yagi array for the determination of the dispersion relation using full-field electrodynamic simulations	10
Figure 2-3 (color): Influence of rod height on the guiding properties of Yagi arrays	10
Figure 2-4 (color): Transmission line model of a Yagi array	11
Figure 2-5: Dispersion relation for electromagnetic waves propagating on a linear Yagi array consisting of 101 copper rods obtained by electromagnetic simulations.....	13
Figure 2-6 (color): Top view of a fabricated 90-degree corner Yagi structure on Styrofoam, showing a source and two probe dipoles	15
Figure 2-7 (color): Guiding energy along a linear Yagi array.....	15
Figure 2-8 (color): Guiding energy along a corner Yagi array.....	17
Figure 2-9 (color): Routing energy in a Yagi tee structure	18
Figure 2-10 (color): Modulation of energy in Yagi arrays	20
Figure 2-11 (color): Power modulation characteristic of a Yagi modulator.....	21
Figure 3-1: Energy flux (Poynting vector) around a metal nanoparticle under plane wave excitation at two frequencies.....	26
Figure 3-2: Extinction of 30 nm Au colloids	27

Figure 3-3: Dipole resonance position for spheroids with different aspect ratios for both the long- and the short-axis mode of excitation	28
Figure 3-4: Energy relaxation of a surface plasmon.....	29
Figure 3-5: Plasmon decay time for Au (a) and Ag (b) nanoparticles.....	31
Figure 3-6: Geometry of a plasmon waveguide consisting of a chain of noble metal nanoparticles	34
Figure 3-7 (color): Dispersion relation of a plasmon waveguide..	36
Figure 3-8 (color): Calculated power transmission coefficients η in plasmon waveguides for a 90-degree corner and a tee structure	38
Figure 3-9 (color): A simulated nanoscale all-optical modulator.....	39
Figure 4-1: Real (lower curves) and imaginary (upper curves) part of the dielectric function of Au from the literature	42
Figure 4-2 (color): Determination of the single particle plasmon resonance frequency... ..	44
Figure 4-3 (color): Collective excitation of a plasmon waveguide.....	46
Figure 4-4 (color): Collective resonance energies of nanoparticle chain arrays.....	47
Figure 4-5 (color): Simulation of a locally excited plasmon waveguide.....	50
Figure 4-6 (color): Dispersion relation of plasmon waveguides obtained using FDTD simulations	51
Figure 4-7 (color): Pulsed local excitation of plasmon waveguides.....	52
Figure 4-8 (color): Energy decay during pulse propagation in plasmon waveguides.....	53
Figure 4-9 (color): Negative phase velocity in plasmon waveguides.....	54
Figure 4-10 (color): Pulse propagation through spheroidal plasmon waveguides.....	56
Figure 4-11 (color): FDTD simulation of a 90-degree corner plasmon waveguide.....	59