The Optical Response of Rectangular Metallic Gratings and Metal/Dielectric Multilayers

Submitted by

Martyn Richard Gadsdon

To the University of Exeter as a thesis for the degree of Doctor of Philosophy in Physics, June 2009.

I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

.... (signature)

Abstract

THE ABILITY OF periodic surface variations to influence and control the electromagnetic response of interfaces and structures has been recognised for many years. Concurrently with these investigations, it has been found that individual particles and wires support interesting electromagnetic resonances. It has also long been established that multi-layer structures of planar interfaces may also result in interesting electromagnetic responses. Multi-layer structures of alternating dielectrics have been shown to produce periodic transmission resonances, however, if one of the dielectrics is replaced with a thin metallic film, it has recently been demonstrated that wide band-pass regions are formed in the electromagnetic response of the structure.

The work presented in this thesis can be considered to be separated into two distinct, but related, areas. One of the areas involves the analysis of wire grid arrays. It is demonstrated that, like the case of deep surface relief perturbations, the waveguide modes in the slits can be considered as the evolution of surface modes on shallow surface relief perturbations. The perturbation effects of the slits on the surface modes and the effect of their excitation on optically thick and thin wires are also investigated. Finally, a new electromagnetic resonance is presented on both 1-dimensional and 2-dimensional wire grid arrays. It is shown that this is closely related to the localised surface modes that have been shown to occur on individual particles and wires. However, the resonance presented is shown to be subtly different from these modes, which typically result in a transmission and reflection extinction, because the planar geometry of the wires and the periodicity result in a reflection enhancement, even when the wires are optically thin.

The second area of this work may be separated into two distinct sub-sections.

The first section examines the electromagnetic response of dielectric/metal multi-layer stacks. These are confirmed to exhibit a periodic series of broad band-pass regions, with the spectral location of these regions being dependent only on the unit cell, not the full extent of the structures. The location of each band-edge of these regions are then demonstrated to be a result of the matching of boundary conditions between standing waves in the cavities having either a *cos* or a *sin* standing wave function, and the evanescent fields inside the metal layers having either a *sinh* or a *cosh* field distribution.

The second section examines the electromagnetic response of continuous surface relief gratings, with a rectangular cross-section, whose ridges are very thin. It is shown that vertical standing waves form, similar to the cavity waveguide modes, except with the fields coupled through the wires not across the grooves. These are then shown to reach a finite limit frequency as the grating height tends to infinity. Thus, the resonances have evolved into a different mode beyond a certain grating amplitude. This mode is shown to to be equivalent to the band-pass region described in multi-layer metal/dielectric stacks. However, scattering and periodicity considerations require that only the low frequency band-edge can be coupled to at normal incidence, while only the high frequency band-edge may be coupled to at grazing incidence.

Contents

List of Figures

Acknowledgements

I HAVE BEEN very fortunate to have undertaken my PhD in such a friendly, personable and high quality research group. Everyone has consistently been welcoming and always willing to help, from sitting down with me to discuss problems I may have had, and graciously offering the benefit of their knowledge and experience, to being prepared to work through experiments/fabrication techniques/theoretical work to ensure I was doing such things correctly.

Of course I must give the first specific mention to my Supervisor, Professor J. Roy Sambles, who generously gave me the opportunity to undertake this doctorate in the first place. Sadly I have heard many horror stories about Supervisors who spend unreasonably small amounts of time with their students, who offer very little in the way of academic insight/understanding, who regularly insist on their students undertaking futile investigations, and who take an extremely long time to return pieces of work that they are to review before publication/presentation causing excessive productivity bottlenecks. As such, I consider myself incredibly lucky to have had Prof. Sambles as my supervisor, his apparently boundless enthusiasm and excitement for science has never ceased to amaze me, I am sure you don't need me to tell you how fortunate science, and physics in particular, has been to have him. Personally, he has always made an effort to ensure I have had more than adequate supervision, by ensuring that he constantly knew the current state of my work, and always made sure I was being productive and heading in a sensible direction, particularly during periods when my motivation could have waned when things were not going as straightforwardly as I wished. I must also thank him for always being prepared to sit down with me to ensure I always fully understood the scientific implications of my results, particularly the more surprising ones. Finally

I must say thank you for the extraordinary speed with which he returned pieces of my work he was reviewing, because this always meant that the only bottleneck in my productivity came from my side. Without him I would certainly not be sat here writing these acknowledgments.

I must also say a huge thank you to Dr Ian Hooper, my surrogate supervisor, who helped me with far too many aspects of my PhD to note down in these acknowledgements; of which these include demonstrating the vast majority of the experimental and fabrication techniques I used, and constantly and patiently explaining all of my questions about every scientific, technical and practical aspect of my PhD (especially the stupid ones). I would also not be writing these acknowledgments if it was not for him. I hope he is enjoying his well deserved break travelling round the world, but I also hope he is given the opportunity to return to academia because I think it would be a shame to lose someone of his quality.

Thanks also to all at Sharp Laboratories of Europe for their financial support and showing me that their is a bigger picture than just academia, especially my industrial supervisor Jonathan Mather.

One of my basement colleagues, Stephen Cornford, must also get a special mention for giving me the benefit of his wisdom on numerous occasions, usually, but not exclusively, of a mathematical and computational nature. If he were to flick through Chapter 3 he'll see a figure that represents a significant simplification of the mathematics I used, and simply wouldn't be there without his advice. Further, I cannot thank him enough for introducing me to the wonderful Ubuntu, Latex, R, and all things open source.

I would also like to thank two members of our technical support staff, Dave Jarvis and Pete Cann. Dave for carrying out many of the evaporations for which I did not have access to appropriate equipment, and for always doing them far quicker than I expected. Pete for helping me out with several technical issues, in particular making many of my substrates, and a clever little angled evaporation mount.

I must also thank my mentor Dr Feodor Ogrin for several useful discussions and comments from an outside perspective.

In no particular order the following members of our group have also helped me in one way or another, be it directly, or simply by imbuing the group with such a friendly and productive atmosphere: Dr Tim Atherton, Dr Tim Taphouse, Dr John Birkett, Dr Sharon Jewell, Dr Alastair Hibbins, Dr Andy Murray, Baptiste Auguié, James Parsons (some may say my partner in crime, but we did talk sensibly about physics on many occasions, just never when we had an audience!), James Edmunds, Dr Matt Lockyear, Ciarán Stewart, Ed Stone, Dr Rob Kelly, Dr Euan Hendry, Dr Pete Vukusic, Prof. Bill Barnes, Prof. Fuzi Yang, Dr Lizhen Ruan, Dr George Zorinyants, Chris Burrows, Tom Isaac, Rich Hartman, Mel Taylor, Joe Noyes, Tomasz Trzeciak, and of course Dr Death and Mr Doom.

From reading several other acknowledgments it appears to be customary at this stage to reveal embarrassing nicknames and to generally dish the dirt on your fellow colleagues. However, I am going to disappoint everyone and break that trend, mainly because I am not witty enough to carry it off particularly well. So, I won't mention Mr Justice, nor will I talk about how shockingly behaved Al, Euan and Sharon were on the conference, while Matt, Rob and myself behaved impeccably, and I most definitely wont mention any of the numerous scrapes and incidents a certain Mr J. Asbo has got himself involved in.

I would like to finish my Exeter acknowledgements with a general warning to new PhD students in our group, or maybe it is more a clarification. Don't worry about the various offensive words that you are bound to have directed at you from Matt, it appears to be a strange sign of affection, perhaps some sort of rite of passage. The only time you need to worry is when he isn't calling you all the names under the sun. Put it this way, I certainly know I didn't feel like I'd truly made it until I was subjected to a torrent of abuse while standing atop a mountain in Austria as a result of a less than salubrious comment on my part!

Thank you all again and good luck to everyone, I will miss both working and socialising with you.

I must now take a brief moment to make a special mention of an old teacher from secondary school (old as in years ago, not as in he is old!), who I really ought to have gone and thanked in person before now. Nigel Bispham, who taught me science from my first day in secondary school, through to my final days as an A-level physics student. I suppose I must have had some natural inclination towards science, and physics in particular, but there is no doubt in my mind that, without him spotting this and then using his extraordinary enthusiasm for teaching science (not to mention his patience in dealing with me!), my love of physics would not have been nurtured as carefully and attentively as it was. I know I'll never forget him explaining exponential growth/decay using the area of his bald spot as a function of the length of time he had been teaching me! When I started university, realising how much effort he had put in to me was one of the significant reasons why I finally pulled my finger out and started trying at, not just enjoying, physics, which was something I had not always done before! It is a cliche, but teachers like him really are worth their weight in gold, I certainly would not have reached the level that brings me to write these acknowledgements without him.

The last section of my acknowledgements must, of course, be devoted to thanking my family. I cannot ever fully explain how appreciative I am for eveything they have done for me, both practically and more intangibly, but I hope a few words here will go some way towards redressing the balance. They have always been hugely encouraging and supportive of my education, even when I chopped and changed what I was doing, making sure I understand the importance of bettering yourself, but importantly, without ever being too pressurising. I have always been free to make my own decisions without feeling I have to do what is expected – without that encouragement yet freedom I would not be here now.

Right, that should be everyone I think. If in the unlikely event that an unmentioned person who deserves thanks is reading this then I apologise sincerely that I have not mentioned you. I hope you realise that the fact I have omitted you does not mean I do not appreciate your help, it just means I have a terrible memory and I hope you take consolation in that fact!

Thank you all again.