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Terahertz Physics

Terahertz physics covers one of the least explored but richest regions of the electromagnetic spectrum. Designed for independent learning, this is the first textbook to open up this exciting new area to students of science and engineering.

Written in a clear and consistent style, the book focusses on an understanding of fundamental physical principles at terahertz frequencies and their applications. Part I outlines the foundations of terahertz science, starting with the mathematical representation of oscillations before exploring terahertz-frequency light, terahertz phenomena in matter and the terahertz interactions between light and matter. Part II covers components of terahertz technology, from sources of terahertz-frequency radiation, through the manipulation of the radiation, to its detection. Part III deals with applications, including time-domain spectroscopy.

Highlighting modern developments and concepts, the book is ideal for self-study. It features precise definitions, clear explanations, instructive illustrations, fully worked examples, numerous exercises and a comprehensive glossary.

R. A. Lewis is a Professor in the School of Physics and the Institute for Superconducting and Electronic Materials at the University of Wollongong, Australia. Lewis is an active researcher in the area of terahertz science and technology.

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To my parents Frank and Julie

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Preface

This book aims to teach. It is directed to students. It is not directed to researchers.

Research literature is typically written in the third person. That is appropriate. In this book I will often write in the first person – there, I just did! – and address you – yes, you, the reader – in the second person. When I employ 'we' it is not as a royal plural, but as you and me together, author and reader, engaged in the common pursuit of applying ourselves to terahertz physics. I hope you are comfortable with, or will become comfortable with, this use of personal pronouns.

This book is a text book. So it contains text. But not unrelieved text. To give pedagogical structure, the text is divided into parts, into chapters, into sections and into subsections. But there is more, to accommodate different learning styles. Perhaps you are a visual learner; there are diagrams for you. Perhaps you are a native speaker of the language of mathematics; equations succinctly express much of the material. Perhaps you learn by example; there are examples sprinkled throughout. Perhaps you learn by doing; there are exercises aplenty. If you like reading dictionaries or telephone directories, you might like the glossary.

Apparatus to facilitate learning is integral to the book. Here is a fuller list of these features:

Assumed mathematics concepts are set out at the beginning of each chapter. The book is about physics, not mathematics, but mathematics is the language of physics, and a prerequisite to understanding much of what is said.

Learning goals near the beginning of each chapter identify the key pedagogical aims.

Examples concretely illustrate abstract concepts.

Exercises provide the opportunity to put new concepts into practice immediately. The exercises appear right where they are pertinent, rather than at the end of the section or at the end of the chapter. Doing the exercises is the best way to learn. I have learnt a lot through them.

Figures are used extensively and often drawn accurately to scale to provide additional information.

Key terms are cited at the end of each chapter, with a page reference to their main appearance.

Key equations are reiterated at the end of each chapter.

Tables of symbols appear at the end of each chapter. The abundance of concepts and the scarcity of symbols inevitably leads to the same symbols being used to

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mean different things. Often the meaning is clear from context. Listing the symbols chapter by chapter reduces the likelihood of symbol confusion.

Glossary An extensive glossary is provided at the back of the book. Glossary terms appear in bold in the main part of the book.

Appendices set out common mathematical symbols used throughout the book, mathematical background material, information about physical quantities and further reading.

Index of many terms. Citations to figures are shown in bold in the index.

All the tools I have to hand – words, pictures, equations – I have employed to try to make my meaning clear. It is not bad that you encounter the same material expressed in words, in pictures, in equations. It is not an oversight. It is a deliberate strategy to assist you to learn. Repetition is the key to learning. Repetition is the key to learning. Whether prose, structure, pictures, equations, examples, exercises, notes or definitions speak most clearly to you, I hope you will find between the covers of this book a path to a greater understanding of terahertz physics.

'Where did that spring from?' is the despairing cry of the bamboozled student who can't fathom how a new topic builds on what has gone before. The sequencing of topics is critical to the pedagogy. I start with the basic and from there advance. For example, oscillations, involving one variable, come first. Waves, involving two variables, wait in the wings until Chapter 4. Purely mathematical concepts precede physical concepts. Physics is about energy and matter and even these are introduced separately, energy in Chapter 4, matter in Chapter 5. I have spent a lot of time thinking about the logical development of the subject so you don't have to give it a second thought.

Terahertz physics is not a completely distinct category of physics, as *nuclear physics* or *quantum physics* are. The idea of terahertz physics is similar to the idea of *high-energy physics*: it simply refers to the physics that obtains in a particular region. Hence terahertz physics does not refer to radically new phenomena, but to the application of the fundamental principles of physics – electromagnetism, mechanics, quantum theory – to a distinct subset of phenomena, namely, those that have characteristic rates of the order of a million million per second. So in studying this book, do not expect to learn fundamentally new physical principles, but expect to apply the physics you may already have in new circumstances. Perhaps you will even better understand some principles you already have a nodding acquaintance with, in seeing them in action in the terahertz region. If, after reading this book, you were to say, 'I never really understood (Fourier theory/dipole radiation/beats/. . .) before, but now I do', I would be delighted.

Thanks to Wendy and Warwick for spurring me on in different ways. Thanks to Joshua and Alaric for their comments. Thanks to Helen for endless love. Thanks to God, for from him and through him and for him are all things. To him be the glory forever! Amen.

R. A. Lewis
Wollongong
20–02–2012

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1 INTRODUCTION

What is meant by frequency and why is it more fundamental than time?

The only mathematics you need to begin with is the ability to count and to perform the basic arithmetical operations of multiply and divide.

1.1 Frequency. Hertz.

The unit of frequency is the hertz. Your heart rate is near to one hertz.

Let's start with the idea of **frequency**. (Rate means the same thing.) Frequency is a key concept and this book is built on it.

Take your pulse. Its frequency is about one hertz. This book is all about things that happen at a much greater rate, at about one terahertz. I will define a terahertz a little later, but for now it is enough to know that it is a rate. Let's begin with something closer to hand, the rate at which your heart pumps your blood through your veins, which you can feel for yourself at your neck or your wrist.

Your heart rate is near to one hertz. If you are resting it might be a tad less. If you get up and run, it might rise to two hertz or even three. You could check the change against a friend who is still at rest. You might find after running you counted twenty pulses for every ten of her pulses, whereas when you were sitting you had measured only twelve pulses for every ten of hers. It is easy to compare rates. No measuring instrument or equipment or apparatus of any kind is required. All you have to do is count.

Rather than test your heart rate against someone, you might calibrate it against something. Galileo is said to have compared his pulse rate to the rate at which a lamp, hanging on a long chain, swung back and forth in the Cathedral at Pisa. Say Galileo counted eight pulses as the chandelier went to then fro. Let's imagine the church bells rang twice as this was happening. Then the rate of Galileo's pulse was eight times the rate of the chandelier swing and the rate of the bells pealing was twice the rate of the chandelier swing. In such manner we can measure various rates. Not only is the order of the rates found – the chandelier the least, next the bells, then the pulse – but the numerical standings are also found – in the ratio one to two to eight. We do all this by counting. We do not need special instrumentation to measure rate.

We have seen that rates relative one to the other can be found out by counting. To go further, it is useful to have a benchmark rate to act as a standard and then to compare

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any other rate with it. My heart rate is most likely different from yours, so human heart rate would not be a well-defined standard. I might decide to ignore you and use my own heart rate as a standard, but I know my heart rate increases with exercise, so this would not be a good choice. We want as a standard something that is independent of a particular implementation and always has the same rate, as far as we can tell. How we can tell the rate is not changing is an interesting question, but we will answer it here by saying we assume or define the standard rate to be unchanging. Here is the standard of rate that will be used in this book:

> The rate of radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom is 9 192 631 770 hertz.

This statement defines the **hertz**. The statement is consistent with the international system of units known as SI although not formally part of it. I don't expect you to follow the technical detail of the definition but you should appreciate two things. First, we are assuming that all caesium 133 atoms are the same – unlike human hearts, which differ from person to person. Second, we are assuming that a caesium 133 atom always radiates at the same rate – unlike human hearts, which pump at a greater rate during exercise than when at rest.

1.2 Time. Second.

The unit of time is the second.

What is **time**? That is a good question. The answer is often not so good. 'Time is the . . . ahh, time . . . between two events'. Look in some dictionaries to see how self-referential and even tautological the definitions of time are.

How does one measure time? Use a clock. An instrument is needed to measure time. This is in contrast to rate, where we have seen that no device, only an ability to count, is needed.

In this book frequency is primary, time is secondary. Time is the inverse of frequency. I have defined the unit of rate, the hertz, already. Now, based on the hertz, I will define the unit of time, the **second**:

> The second is the inverse of the hertz.

By this I mean time [in seconds] multiplied by the rate [in hertz] amounts to one. So a heart rate of one hertz corresponds to a time between pulses of one second. A heart rate of two hertz corresponds to a time between pulses of half a second. As one quantity goes up, the other goes down; the product remains the same. This inverse relation may appear trivial but it has profound consequences. It would not be an exaggeration to say that much of this book turns on the inverse relation between frequency and time.

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1.3 Wavelength. Metres.

A wave has a particular length. It is called the wavelength. It is measured in metres.

I won't go into what is meant by a wave here (that is explained later) except to say that it has a characteristic length. This is the distance between two points on the wave that behave identically, for example, between two successive crests or between two successive troughs of an ocean wave. This distance is the **wavelength**.

Light has a wave nature. For light in empty space, the product of the wavelength and the frequency is constant. From this, we can define the unit of length, the **metre**:

The metre is the wavelength, in a vacuum, of light of frequency 299 792 458 hertz.

This definition is consistent with the SI definition, albeit expressed differently.

A convenient multiple of the metre is often used when discussing waves. For example, millimetre waves refer to waves of wavelength about one thousandth of a metre. The field of terahertz is sometimes identified with millimetre or with sub-millimetre waves.

1.4 Wavenumber. Inverse metres.

The wavenumber says how many waves there are in a given length.

How many waves there are in a given distance can be counted or numbered, and this is the origin of the word **wavenumber**.

A metric ruler is usually marked in millimetres and centimetres. There are typically nine strokes denoting the millimetres between two larger strokes marking successive centimetres, so over any portion of the ruler one centimetre in length there are ten strokes. The strokes are found at the rate of ten per centimetre. We say the linear frequency or spatial frequency of strokes is ten per centimetre, or ten inverse centimetres.

The SI unit for wavenumber is (number) per metre, or **inverse metre**. In spectroscopy – and there is some spectroscopy in this book – it has been traditional to count the number of waves per centimetre, rather than per metre. So you will often see the unit of inverse centimetre employed in specifying wavenumber. (Some people call the unit of inverse centimetre itself the wavenumber. I mention this only so that you are aware of it. I will avoid this usage in this book, however, as it opens the gate to confusion.) It may seem redundant, but for completeness let's define the unit for measuring wavenumbers:

The inverse metre is the inverse of the metre.

Example 1.1 Heartbeats

A mouse has a heart rate of 10 hertz. The time between heartbeats in an elephant is 2 seconds. How much greater is the mouse's heart rate than the elephant's?

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Solution

We convert the time information given for the elephant into a rate. Taking the inverse of 2 seconds, we arrive at 0.5 (the inverse of 2) hertz (the inverse of seconds). Thus the ratio of heart rates is 10/0.5 = 20. *Aside: The life span of many mammals is about one thousand million heartbeats. An elephant lives about 20 times as long as a mouse.*

1.5 Powers of ten

I have mentioned in passing 'millimetres' and 'centimetres'. I expect you already knew, or have gathered, a millimetre is one thousandth of a metre and a centimetre is one hundredth of a metre. The prefixes 'milli' and 'centi' are examples of a shorthand way to represent powers of ten. A full list of SI prefixes is given in Appendix A.

As far as this book is concerned, the most important power of ten is ten raised to the power of twelve, or 10^{12}. This is given the prefix 'tera'. This book is about the **terahertz**:

$$1 \text{ terahertz} \equiv 10^{12} \text{ hertz.}$$

This is the definition of the terahertz. I use the symbol '≡' to stand for 'is defined to be'. (It is stronger than '=', which means is 'equal to'. One terahertz does not just happen to be the same as 10^{12} hertz at the moment; it always is 10^{12} hertz.)

You can consult Appendix A to find many equivalent ways to express one terahertz. Here are some that are in common use:

$$1 \text{ terahertz} = 1\,000 \text{ gigahertz} = 1\,000\,000 \text{ megahertz.}$$

So a terahertz is a 'megamegahertz', meaning a million million hertz. That's a lot of hertz.

Exercise 1.1 Wavelength-wavenumber product

Show that the product of the wavelength, when expressed in micrometres, and the wavenumber, when expressed in inverse centimetres, is always 10 000. ■

1.6 Quantities, symbols, units, dimensions

The only mathematics needed in this section – apart from the ability to count, to multiply and to divide – is basic algebra; that is, the ability to represent quantities by symbols.

We have met four quantities: frequency, time, wavelength and wavenumber. Rather than write these words out in full each time, it is easier to abbreviate each to a symbol. The simplest symbols are single characters. The characters I will use are set out in Table 1.1.

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Table 1.1 Basic quantities and symbols

Quantity	Symbol
frequency	f
time	t
wavelength	λ
wavenumber	σ

The symbols are all shown in italic font. This is to better distinguish them from normal words. The symbols for frequency and time are rather straightforward in origin, being the first letters of those two words. The symbol for wavelength is the Greek letter lambda, the equivalent of the English letter 'l', which is associated with the first letter of 'length'. The symbol for wavenumber is the Greek letter sigma, the equivalent of the English letter 's'; the origin of the association is obscure.

The symbols save space, but at a cost. There are only a few different characters (compared to the huge number of words) and at different times the same character is used to represent different things. So t might be used to represent thickness and not time in another context. You need to take care with this.

When symbols represent physical properties, the symbols represent not only the numerical value of the quantity but also its unit. The symbols carry these two separate things. For example, f may represent '10 hertz'; both the quantity, here 10, and the unit, here hertz, are bound up in the single character f.

Apart from compactness, a second advantage of using symbols for quantities is that the symbols lend themselves easily to mathematical manipulation. This is known as 'quantity calculus'. So, rather than write 'inverse of the rate', I can write $1/f$, and calculate, for example, for a rate of 2 hertz,

$$\frac{1}{f} = \frac{1}{2\,\text{hertz}} = \frac{1}{2} \times \frac{1}{\text{hertz}} = 0.5\,\text{seconds}.$$

Notice that the units are bound up in the calculation. The answer, in this case, is in units of inverse hertz, or seconds.

Sometimes I will explicitly show the units that I am using. I will do this using square brackets, such as [in hertz]. For example,

$$\lambda\,[\text{in metres}] = \frac{1}{\sigma\,[\text{in inverse metres}]}.$$

Multiplying on both sides by the denominator,

$$\lambda\,[\text{in metres}] \times \sigma\,[\text{in inverse metres}] = 1[\text{unitless}],$$

where the notation [unitless] indicates a quantity without units, or a simple number. (Quantities like this, with no units, are called 'dimensionless quantities' or 'quantities of dimension one'.) I am most likely to show the units explicitly if I am using units that are not the usual SI units.

Just as we can use a compact notation to write quantities, we can use a compact notation to write units. The four key units and their abbreviations are set out in Table 1.2.

Notice these compact ways of writing the units are not in italic font. This distinguishes them from quantities. Still, there is a chance for confusion, for example if 'm'

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Unit	Abbreviation
hertz	Hz
second	s
metre	m
inverse metre	m^{-1}

Table 1.2 Basic units and abbreviations

is used to represent the unit of metre and *m* has been chosen to represent the quantity of mass. Take care!

The unit 'hertz', when written out in full, begins with a lower-case 'h', but when abbreviated as 'Hz' begins with an upper-case 'H'.

The power-of-ten prefixes used with units also have abbreviated forms. For example, the prefix 'mega', meaning one million, is abbreviated as 'M'. A full list is given in Appendix A.

In stating numerical values given with units, a space should be left between the two. So, write '5 THz', not '5THz'.

Using the abbreviations for prefixes and units, we may more compactly write

$$1\,\mathrm{THz} = 1\,000\,\mathrm{GHz} = 1\,000\,000\,\mathrm{MHz}.$$

Apart from the physical quantity itself and its units, and how to express these in compact, symbolic forms, it is useful to be aware of dimensions. For example, wavelength has the dimension of length, which we indicate by the sans serif font L. Wavenumber has the dimension of inverse length (L^{-1}). We may assign to frequency the dimension F. Then time will have the dimension F^{-1}.

1.7 What lies ahead

I hope you now have a feel for the quantities of frequency and wavelength, and their inverses, time and wavenumber. Frequency is associated with oscillations. Wavelength is associated with waves. Much of the book is concerned with these two topics.

Now is a good time to give an outline of the rest of the book.

Part I Basics Part I lays the foundation for the rest of the book. Oscillations are the subject of Chapters 2 and 3. Chapter 2 provides a framework for dealing with oscillations. Chapter 3 explains how oscillations are combined. These foundational chapters are largely mathematical in character. On to physics. Physics is about energy and matter and their interaction. Chapter 4 introduces energy in its purest form – light. Chapter 5 introduces matter and the phenomena that occur in matter at terahertz frequencies. Chapter 6 deals with the interaction of light and matter. Chapter 3 is built on Chapter 2; Chapter 4 is built on both of these, as is Chapter 5; Chapter 6 is built on Chapters 4 and 5.

Part II Components Part II describes the building blocks that make up practical terahertz systems. We start with the sources of terahertz-frequency electromagnetic radiation in Chapter 7. As the terahertz radiation propagates, it can be manipulated by various optics, the subject of Chapter 8. Finally, Chapter 9 deals with

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the radiation being detected at its journey's end. These three chapters may be read independently of each other, but all depend on the foundation of Part I.

Part III Applications Part III describes two important areas of application of terahertz technology. Chapter 10 describes spectroscopy. Chapter 11 describes imaging. These chapters may be read independently of each other, but are each based on the terahertz components described in Part II.

From the way I have set this out, you may think of a building going up and being used: Part I is about the foundations that underpin the whole structure; Part II is about the bricks and mortar that together constitute the building; Part III is about the uses to which the finished premises are finally put.

Or think of a tree. Part I is like the roots, often unseen, but sustaining the rest. Part II is like the leaves and branches, what we take as the tree. Part III is like the fruit, the product of the whole.

1.8 Summary

We have met four physical quantities: frequency, time, wavelength and wavenumber. Each may be represented by a simple symbol. Each has a unit and a dimension. (We have also met the abbreviated units and prefixes for units.) Table 1.3 summarises these.

Table 1.3 Summary of basic physical quantities

Quantity		Unit		Dimension	
frequency	f	hertz	Hz	frequency	F
time	t	second	s	inverse frequency	F^{-1}
wavelength	λ	metre	m	length	L
wavenumber	σ	inverse metre	m^{-1}	inverse length	L^{-1}

This book is all about things that happen at a rate of about one terahertz:

$$1\,\mathrm{THz} \equiv 10^{12}\,\mathrm{Hz} = 1\,000\,\mathrm{GHz} = 1\,000\,000\,\mathrm{MHz}.$$

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