Non-Drude like behaviour of metals in the terahertz spectral range

Shashank Pandey, Barun Gupta, Ashish Chanana and Ajay Nahata

Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT, USA

ABSTRACT
We review measurements of the dielectric properties of metals, which have resurfaced as a timely topic given the ongoing interest in plasmonics across a broad range of the electromagnetic spectrum. It is generally accepted that the Drude model fully describes the optical response of metals. This is certainly true at optical frequencies. This also appears to be the case when THz time-domain spectroscopy is used to measure the properties of thin films. However, for a variety of plasmonics-based implementations in the terahertz (THz) spectral range, there appear to be significant discrepancies. We discuss these observations, as well as a new family of measurement techniques based on the excitation and detection of surface plasmon-polaritons. Finally, we conclude with a brief discussion regarding the implications of these new measurements for the field of THz plasmonics.

1. Introduction
Understanding and fully characterizing the dielectric properties of materials is central to controlling the propagation properties of light and has direct impact on
the functionality and performance of optical devices. Such devices often incorporate a variety of different materials, including dielectrics, semiconductors and metals. At visible frequencies, measuring the optical properties of dielectrics is relatively straightforward and can be readily accomplished using a variety of well-established techniques, including transmission and reflection measurements, waveguide measurements, Fourier spectroscopy and ellipsometry [1]. Measuring these properties for metals and highly doped semiconductors, on the other hand, is typically more challenging. Ellipsometry has been shown to work well for these materials, although models to fit the data are needed in order to extract the refractive index information. Nevertheless, this technique is sensitive to changes in the dielectric properties of the medium that occur with variations in deposition conditions [2], environmental exposure [3] and the crystalline nature of the metal film [4]. Despite these variations, the dielectric properties of most conventional metals can be well described by the Drude model at optical frequencies. This is due to the fact that the bulk plasma frequency, which lies in the ultraviolet frequency range for these materials, is in close spectral proximity to the interrogating wavelength. The fact that the dielectric properties can be modelled with a high degree of accuracy at optical frequencies has been particularly beneficial for the field of plasmonics, which relies on the interaction between electromagnetic fields and (structured) metal films via the excitation of both surface plasmon-polaritons (SPPs) and localized surface plasmons. Indeed, the availability of an analytical model for the optical constants of metals has allowed for more straightforward prediction of new phenomena.

It is generally assumed that the Drude model is a valid description of the dielectric properties for metals (free electron model) across the entire electromagnetic spectrum. This assumption simplifies matters, since measurement of the optical properties of metals becomes increasingly difficult in the long-wavelength regime. In this review, we will focus on the dielectric properties of metals at terahertz (THz) frequencies, a spectral band that has elicited significantly greater attention in recent years, not only for fundamental studies, but also because of the applicability to device and systems applications in high-speed computing and communications. We begin by discussing the history of these measurements, first at visible wavelengths and then in the long-wavelength regime. This is followed by a description of a number of recent measurements that are not consistent with predictions based on the Drude model. These inconsistencies have prompted the development of a new family of measurement techniques that appear to yield dramatically different refractive index properties for the same conventional metals. Based on these new findings, we conclude by discussing the implications of these revised optical constants on prior work and the need for new theoretical and experimental work to explain these contradictory results.
2. Optical constants of metals

Optical constants of metals have been measured since the time of Drude, with many of the earliest measurements utilizing a polarimetric technique [5]. While the approach yielded both the real and imaginary components of the refractive index, it was extremely sensitive to the surface preparation of the film. Interference techniques were also used, but they required careful fabrication of interference filters using thin mica sheets [6]. In the infrared, a calorimetric technique was developed in which the sample was irradiated with visible radiation and the reflected energy was absorbed by an Au-black absorber [7]. An advantage of the approach was that it could accurately measure the absorptivity spectra. As computational capabilities increased, transmission and reflection measurements became increasingly popular [8–10]. However, these measurement schemes rely on the use of Kramers–Kronig transformations to extract both the real and imaginary optical constants. In order to utilize this transform properly, the measurement data have to be extrapolated well beyond the measured spectral range and the details of that extrapolation can have significant impact on the magnitude of the extracted constants. This issue can be reduced, to some extent, by performing measurements at multiple angles, thereby increasing the accuracy of the extracted data [8]. Today, ellipsometry is perhaps the most popular measurement technique for measuring the refractive indices of a broad range of materials. While numerical models are needed to extract refractive index information from the measured data, a wide range of models have been developed over time and are commonly available.

In contrast to the numerous techniques that have been utilized to obtain the dielectric properties of metals at optical frequencies, relatively few of these have been used in the THz spectral range. Brändli and Sievers created an array of parallel plate waveguides in which thin layers of Au or Pb were deposited on dielectric substrates and the intensity of the transmitted far-infrared radiation was measured [11]. By assuming TEM wave propagation and modelling the waveguide impedance properties, they were able to extract the surface resistance properties of the metals out beyond 100 cm⁻¹ (1 THz = 33.3 cm⁻¹), which, in turn, could be used to obtain the optical constants. However, few other metals were measured at such low frequencies at the time. In fact, one of the most commonly used references for dielectric properties of metals in the far-infrared that often serves as a compendium of prior work in the area shows only low-frequency (less than a few hundred to ~1000 cm⁻¹) dielectric measurements for Au and Pb [11]. Nevertheless, the dielectric properties for a wide range of metals are shown using extrapolations based on the Drude model. In Figure 1, we show the real and imaginary components of the complex dielectric constant, obtained using the Drude model and fit parameters from [12]. Since the Drude model relies on a plasma frequency that lies in the ultraviolet, the extrapolated real and imaginary components of the dielectric constant tend to be orders of magnitude larger than
the equivalent values at optical frequencies. We discuss the implications of such large dielectric constants below.

In recent years, the issue of metal dielectric properties in the far-infrared has been revisited, although this time using THz time-domain spectroscopy (THz TDS). A significant advantage of this approach, over those mentioned earlier, is that the THz electric field is measured rather than the THz power, so both amplitude and phase information is obtained [13]. Therefore, Kramers–Kronig techniques are not necessary to independently obtain the real and imaginary

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Figure 1. Dielectric properties for Au and Al at THz frequencies based on published data [12], assuming $\varepsilon_0 = 1$. (a) The real component of the dielectric constant ($\varepsilon_{mr}$) based on a Drude model fit (b) The imaginary component of the dielectric constant ($\varepsilon_{mi}$) based on a Drude model fit. Reprinted with permission from [51]. Copyright 2013, OSA.

Figure 2. The measured complex refractive of Au measured for a thin film deposited on a GaAs wafer and measured in transmission using THz time-domain spectroscopy. (a) Real component of the refractive index (b) Imaginary component of the refractive index. Reprinted with permission from [14]. Copyright 2008, the Japan Society of Applied Physics.
components of the refractive index. Both transmission and reflection THz TDS measurements have been performed using either a thin metal film deposited on a substrate or thin metal films placed in a multilayer stack [14–18]. In general, the optical constants obtained from these independent measurements appear to match predictions of the Drude model well, as shown in Figure 2 for data obtained from transmission measurements with thin metal films. Laman and Grischkowsky found that while the Drude model fit their data reasonably well over their measurement range, the conductivity of the thin films was less than values published for bulk metals, particularly at cryogenic temperatures. They attributed this to the role of grain boundaries and defects [18].

3. Implications of metal dielectric properties for plasmonics

In recent years, the increased research activity in the field of plasmonics has led to renewed interest both in accurately measuring the optical properties of metals and in creating metal films that exhibit optimized properties. Aside from concerns regarding propagation losses, which are relevant in all areas of optics, many unique plasmonics phenomena [19–21] depend sensitively upon these parameters. In order to understand how the optical constants affect the properties of SPPs, we first discuss their spatial properties.

In contrast to freely propagating radiation, the dispersion relation for SPP waves on a planar metal film is related to the dielectric properties of the metal and the adjacent dielectric medium and can be written as [22]:

\[ k_x = k_{xr} + i k_{xi} = \frac{\omega}{c} \left( 1 - \frac{\epsilon_d \epsilon_m}{\epsilon_d + \epsilon_m} \right)^{1/2} = \frac{\omega}{c} n_{SPP}, \]

(1)

where \( k_x = k_{xr} + i k_{xi} \) is the complex propagation constant of the SPP wave parallel to the propagation direction \( x \), \( \omega \) is the radial frequency of the electromagnetic radiation, \( c \) is the speed of light in vacuum, \( \epsilon_d \) is the dielectric constant of the dielectric interface medium and \( \epsilon_m \) is the complex dielectric constant of the metal. As SPPs propagate along a metal–dielectric interface, their amplitude decays due to absorption and we can define a 1/e attenuation length along the direction of propagation, \( L_x \), which is given by

\[ L_x = \frac{1}{2|k_{xi}|}. \]

(2)

Since SPPs are bound to the metal–dielectric interface, they decay exponentially away from the metal–dielectric interface along the \( z \)-axis and, therefore, take on their maximum amplitude at the interface. The propagation constant for SPPs within the dielectric medium can be written as [22]:
Once again, we can define a $1/e$ attenuation length into the dielectric, $L_z$, which is given by:

$$L_z = \frac{1}{|k_{zi}|}.$$  

(4)

The coordinate system and the corresponding attenuation lengths are shown in Figure 3.

Figure 3. Schematic drawing of the exponential dependence of SPPs away from a metal–dielectric interface. As an SPP wave propagates to the right along the $x$-axis, it exponentially decays into the dielectric, along the $z$-axis, with a $1/e$ decay length of $L_z$ and also along the $x$-axis with a $1/e$ decay length of $L_x$.

If we now consider SPPs on gold at ~800 nm with air as the dielectric, the dielectric constant according to Johnson and Christy is given by $\varepsilon = -25.8 + 1.6i$ [8]. The corresponding $1/e$ decay length along the metal film is then $L_x = 50 \mu m$ ($\sim 16\lambda$), while $L_z = 81 \text{ nm} \, (\sim \lambda/10)$. On the other hand, at a frequency of 0.5 THz ($\lambda = 600 \mu m$), $\varepsilon = -1.12 \times 10^5 + 1.46 \times 10^6i$ for gold based on predictions from the Drude model [12]. In this case, $L_x = 140 \text{ m} \, (\sim 2.3 \times 10^5\lambda)$, while $L_z = 15 \text{ cm} \, (\sim 250\lambda)$. The fact that SPPs are more tightly bound to the metal–dielectric interface (i.e. SPPs interact with the metal more at optical frequencies than at THz frequencies) corresponds to a shorter propagation length $L_x$ and a correspondingly shorter $L_z$ than at THz frequencies, even when stated in wavelengths. In the case of SPPs at THz frequencies, the numerical value of $L_z$ usually gives rise to the common perception that SPPs are very loosely bound to the metal surface and, thus, cannot exist at THz frequencies.

Based on this perception of loosely bound surface waves, Pendry and co-workers examined perfect conductors that were perforated with a periodic array of through holes [23, 24]. In a planar (unperforated) perfect conductor, the electric field cannot penetrate into the metal. However, with the addition of the
perforations into the medium, they found that surface waves, which they termed spoof surface plasmons, could exist. These spoof plasmons have properties that mimic the dispersion and spatial properties of surface plasmons in real metals. Moreover, the medium can be described by a dielectric function with an effective plasma frequency that is determined only by the geometry of the holes. Thus, the effective plasma frequency can be designed to occur over a broad spectral range, including microwave or THz frequencies.

Since then, many investigators have begun referring to SPPs at THz frequencies as spoof surface plasmons [25–35], even though the terminology is only valid for perfect conductors and not real metals. Nevertheless, the analysis by Pendry et al. does give important insight into the effective dielectric properties of metals in the THz spectral range [23, 24]. While the measured effective dielectric function of structured metals is complex and not purely real as predicted by their theory, it can be described by an effective plasma frequency that is determined by the geometry of the metal structuring [36].

4. Plasmonic measurements at odds with predictions

As noted in the last section, the concept of spoof surface plasmons has been widely applied to plasmonic structures designed for the THz spectral range. Based on this notion, unstructured metals should not be able to support the propagation of surface waves in this frequency range. However, that is not the case. In 2004, Wang and Mittleman showed that broadband radiation could be launched onto unstructured metal wires with low loss bound mode propagation [37]. This propagating mode was first predicted by Sommerfeld [38] and was studied at even lower frequencies (microwaves) in the 1950s [39–41]. Since then, a number of groups have shown that bound surface waves can propagate over distances up to 10–20 cm on a variety of different metals sheets and wires over a broad range of THz frequencies [42–53].

When plasmonic devices are simulated using a variety of numerical electromagnetic software packages, metals are commonly modelled using a perfect electrical conductor (PEC) approximation. This is equivalent to assuming that it is a spoof surface plasmon-based device. In these simulations, the predicted spectral features are always much narrower than those measured experimentally [54, 55]. This discrepancy obviously arises because a PEC approximation does not account for absorption loss that exists with real metals.

Over the last decade, there have been numerous experimental studies that have been shown to be inconsistent with the quantitative predictions for SPPs, when the Drude model is used. We discuss these separately in terms of the measured parameters that differ. The large real and imaginary components of the dielectric constant for a variety of conventional metals suggest that the surface plasmon phase velocity should only differ by a few parts in 10⁸ from the speed of light in vacuum below 1 THz [12]. However, Wang and Mittleman showed a much
larger discrepancy for SPP propagation on metal wires, as shown in Figure 4. In fact, they observed a departure in the measured phase velocity as a function of the wire diameter that was larger than what they computed using the Drude model [45]. Similar discrepancies are discussed below in the context of THz TDS measurements [51].

As we noted earlier, the predicted out-of-plane exponential decay of SPPs is characterized by an $L_z \sim 10–15$ cm at frequencies of ~0.5 THz in a variety of conventional metals. However, Astley and co-workers found that for a 1.75-mm-diameter wire waveguide, there was ~20% transmission when the propagating mode travelled through 3 cm radius of curvature bend [56]. Such a loosely bounded wave would not exhibit such high transmissivity through a comparatively small radius of curvature bend. Jeon and Grischkowsky launched SPPs onto a metal sheet with a curve in it, as shown in Figure 5, and separated the freely propagating THz wave from the bound mode SPPs. By placing a metal block at variable distances above the metal sheet [44], they found that the propagating SPPs were more tightly bound than theory predicted (an out-of-plane $1/e$ decay length of 7.6 mm, which was 28 times smaller than the predicted value of 21.5 cm). Recently, Pandey et al. directly measured $L_z$ by launching SPPs on a variety of different planar metal films and measured the SPP properties via an electro-optic detection technique. They found that at 0.5 THz, $L_z$ (Au) = 3.2 mm, $L_z$ (Al) = 2.9 mm and $L_z$ (stainless steel) = 1.4 mm [51]. Using a somewhat analogous approach, Gerasimov et al. measured a value of ~1.5 mm at 2.3 THz for a gold film [50].

As we also discussed earlier, the predicted in-plane exponential decay of SPPs is characterized by an $L_x > 100$ m at frequencies of ~0.5 THz in a
A variety of conventional metals, corresponding to an attenuation coefficient of $\alpha = 0.0001 \text{ cm}^{-1}$. In the case of wire waveguides, Deibel and co-workers measured an attenuation value that was nearly 300 times higher ($\alpha = 0.03 \text{ cm}^{-1}$) than the predicted value [47]. For planar metal films, Jeon and Grischkowsky measured a $1/e$ propagation length that was nearly 900 times shorter than predicted from the Drude theory at 0.4 THz (0.43 m instead of the predicted value of 385 m) [44]. Pandey et al. also measured this parameter on a variety of different metal films and found $L_x (\text{Au}) = 16.4 \text{ cm}$, $L_x (\text{Al}) = 14.7 \text{ cm}$ and $L_x (\text{stainless steel}) = 6.3 \text{ cm}$ [51], while Gerasimov et al. measured a value of $\sim 10 \text{ cm}$ at 2.3 THz for a gold film [50].
Measurement of the optical constants of metals via the excitation of SPPs

Over the last several years, several new approaches have been developed to measure the optical constants of metals based on the excitation and subsequent detection of SPPs as they propagate along the interface of the metallic medium being investigated and air. In contrast to free space measurements, where the interaction length corresponds to the metal film thickness (in the order of 10s of nm) for transmission measurements or the metal skin depth (δ ~ 100–150 nm) in reflection measurements, the interaction length using SPPs can be 10s of cm or longer.

The basic idea is shown schematically in Figure 6 [50]. Using a free electron laser operating at 2.3 THz, Gerasimov and co-workers launched SPPs onto a flat metallic surface. The interaction length can be several centimeters or longer, enabling precise measurements.

Figure 6. Schematic diagram used to measure the dielectric properties of a gold-coated aluminum plate. A free electron laser (FEL) operating at 2.3 THz is used to generate SPPs using a prism. The sample can be moved to vary the distance between the SPP coupling point and the Golay cell detector. Reprinted with permission from [50]. Copyright 2011, AIP Publishing LLC.

Figure 7. Schematic diagram of the excitation and detection scheme for measurement of the SPP propagation and sample dielectric properties. Broadband THz radiation is normally incident on a 2-cm-long rectangular cross section groove that is 300 μm wide by 100 μm deep. The groove is used to couple normally incident freely propagating broadband THz radiation into SPP waves that propagate along the sample surface. A <1 1 0> ZnTe crystal that can be freely positioned anywhere above the sample surface is used to measure the z-component of the THz electric field via electro-optic sampling. Reprinted with permission from [51]. Copyright 2013, OSA.

5. Measurement of the optical constants of metals via the excitation of SPPs
gold-coated aluminium plate using a prism and measured the transmitted THz power using a Golay cell. By measuring the exponential decay of the SPPs, both in-plane (across ~8 cm length) and out-of-plane (across ~4 cm height), they found that the permittivity of the deposited gold film was $\varepsilon = -877 + 610i$ at the source frequency (2.3 THz).

Pandey and co-workers independently developed a similar approach that utilized the attractive features of THz TDS [51]. In their experimental set-up, shown in Figure 7, they used a simple straight groove etched into a metal plate to couple normally incident broadband THz radiation into SPPs, which then propagated along the surface of several different metal films. The time-domain properties of the THz electric field could then be measured at any point along the propagation direction or normal to the surface via electro-optic sampling [57]. This approach offers an additional means of checking the real component of the measured refractive index: measurement of the time-domain THz waveforms at two different distances along the propagation direction yields a propagation time delay that can be measured with very high temporal resolution and can be used to calculate the real part of $n_{SPP}$ (from Equation (1)).

Figure 8(a) shows two measured time-domain waveforms for distances separated by 10 cm along the propagation axis on a gold-coated metal foil. The observed time delay of 133 fs, with minimal pulse reshaping between the two waveforms, corresponded to a real component of $n_{SPP} = 1.0004$. Based on the Drude model for gold [12] and Equation (1), the real component of $n_{SPP}$ is expected to be 1.000000026, corresponding to a time delay of 0.0087 fs. As noted earlier, both amplitude and phase information are available in this measurement technique for both points along the $x$-axis, as shown in Figure 8(b). Using this data, the complex values of $n_{SPP}$ and the permittivity of the metal were obtained as a function of frequency, as shown in Figures 8(c) and (d), respectively. These data were then used to calculate the values of $L_x$ and $L_z$ as a function of frequency, as shown in Figures 8(e) and (f). In those figures, the discrete points correspond to separate measurements of the decay lengths at a number of points along both axes measured via electro-optic sampling. The agreement in both sets of data is excellent, demonstrating that it is self-consistent. For ease of comparison, we provide tabulated values of $\varepsilon$ measured here and predicted through use of the Drude model in Table 1. As noted earlier, the latter data are in good general agreement with transmission and reflection measurements measured using THz TDS.

This approach is not limited to measuring only the optical constants of metals. Using an experimental system similar to that used in [50], Nazarov and co-workers recently measured the complex permittivity of heavily doped silicon from ~0.1–1 THz, as shown in Figure 9 [53]. They also found that their results did not match the predictions of the Drude model, not only in the magnitude, but also in the variation with frequency. However, since they first launched SPPs onto metal films that later propagated along the doped silicon surface, they attributed the discrepancies in their measured optical constant data to the fact that SPP
propagation lengths in metals were much shorter than expected. It is worth noting that such measurements are extremely important, especially in the case of heavily

**Figure 8.** SPP propagation and dielectric properties for Au. (a) Measured THz time-domain waveforms for two positions separated by 10 cm on the Au-coated metal sheet. The time shift arises from the difference in propagation velocities between the THz SPP and the optical probe pulses. (b) The corresponding amplitude and phase spectra. (c) The extracted values of $n$ and $\kappa$. (d) The calculated values of the real ($\varepsilon_{mr}$) and imaginary ($\varepsilon_{mi}$) components of the dielectric function. (e) Comparison between the $1/e$ propagation length along the x-axis computed from $\varepsilon_{m}$ (solid line) with $\varepsilon_d = 1$ and measurements obtained by taking measurements along the x-axis. (f) Comparison between the $1/e$ decay length along the z-axis computed from $\varepsilon_{m}$ (solid line) with $\varepsilon_d = 1$ and values obtained by taking measurements along the z-axis. Reprinted with permission from [51]. Copyright 2013, OSA.
Table 1. Comparison of dielectric constants for gold from obtained from Drude model [12] and THz SPP-based [51] measurements.

| $f$ (THz) | $\varepsilon$ (Drude model) | $\varepsilon$ (THz SPP) |
|-----------|-----------------------------|-------------------------|
| 0.2       | $-2.47 \times 10^5 + i5.93 \times 10^6$ | $-820 + i587$ |
| 0.4       | $-2.47 \times 10^5 + i2.72 \times 10^6$ | $-812 + i576$ |
| 0.6       | $-2.47 \times 10^5 + i1.84 \times 10^6$ | $-806 + i567$ |
| 0.8       | $-2.46 \times 10^5 + i1.33 \times 10^6$ | $-801 + i560$ |
| 1.0       | $-2.39 \times 10^5 + i1.06 \times 10^6$ | $-797 + i553$ |
| 1.2       | $-2.33 \times 10^5 + i0.86 \times 10^6$ | $-794 + i546$ |

Note: The THz transmission measurements [14] yield dielectric properties that are similar to those obtained from the Drude model.

Figure 9. Measurement of the (a) imaginary and (b) real parts of the surface dielectric function of doped Si, together with error bars. The Drude model value for sample 2 is also plotted (bold line). Reprinted with permission from [53]. Copyright 2015, IEEE.

doped semiconductors, since they have been used in a number of passive and active THz plasmonics implementations [58–60].
At this point, the obvious question that arises pertains to why such a discrepancy exists between the Drude model and free space THz TDS measurements, which appear to be generally consistent, and a number of different SPP-based measurements, which also appear to be generally consistent. Several possible explanations have been suggested. In [50], the authors suggest that the deviations may arise from the fact that the surface and bulk properties of metals are different. However, in both free space and SPP measurements techniques, the penetration depth of the THz electric field is limited by the skin depth. The discrepancy between the measured SPP propagation values and the Drude predictions has been conjectured to be because of radiative or diffraction loss [50, 52]. While the diffractive and radiative properties of SPPs are certainly expected to be different than freely propagating THz radiation, the time delay between THz waveforms measured in [51] does not depend sensitively on loss, as long as there is minimal pulse reshaping, and is consistent with the measured dielectric properties. In addition, the issue of surface roughness has been brought up as a potential reason for the dramatically smaller dielectric values. In all of the SPP-based measurements, thick slabs of different metals or gold that was vacuum deposited onto the metal slabs were used. In [51], the underlying metal sheet was found to have a surface roughness of <3 μm rms, corresponding to λ/200 at 0.5 THz. This is a factor of 10 less roughness than is typically specified for optical grade substrates (λ/20) on which metal films are deposited for optical measurements. Finally, there is the issue of the crystal structure of the metal itself. In almost all of the aforementioned studies, both at optical and THz frequencies, there appears to be no mention of special attention being paid to film deposition conditions. Thus, all of the metal surfaces were all likely to be polycrystalline in nature with wide variation in grain size.

6. Implications of these revised dielectric properties

It is common in theoretical treatments and numerical simulations of devices that incorporate metals to treat them as PECs. This is routinely done because it greatly simplifies the analysis and, as discussed earlier, is a reasonable approximation to the Drude model prediction. In the case of plasmonic devices, this is equivalent to assuming that the device can only support spoof surface plasmons. To show the effect that such assumptions can have on prediction for real devices, we consider the case of plasmonic waveguides designed for THz frequencies.

Kumar and co-workers showed that when a metal slab was partially perforated with a one-dimensional periodic array of rectangular blind holes (i.e. holes that did not completely perforate the metal substrate), the structure behaved as a waveguide that supported relatively low loss propagation of several narrow THz frequency bands [52]. When the device was simulated using numerical finite-difference time-domain techniques and a perfect electrical conductor approximation, a number of resonances were clearly evident and the resonance frequencies could be directly related to geometrical parameters of the individual apertures. They
fabricated devices with the same geometrical properties and used the same THz excitation conditions as in the simulations. The results of these two characterization approaches are shown in Figure 10 for a hole depth of 635 µm. The amplitude spectra have some very clear similarities and differences. Both amplitude spectra have approximately the same resonances and the dips on the high-frequency sides of each resonance occur at the same frequency. However, the linewidth of each resonance associated with the experimental measurements is much larger than that obtained from simulations. This occurred because the metals did not have any absorption loss. If we now use the dielectric properties associated with stainless steel [51] for the device, the resulting amplitude spectrum, also shown in Figure 10, yields much better agreement with experimental results, as expected because of the introduction of loss. Nevertheless, the simulated linewidths are still slightly narrower than those obtained experimentally. This small difference may be associated

Figure 10. (a) Schematic drawing of the planar THz waveguide. The geometrical parameters of the device were \( s = 500 \, \mu\text{m} \), \( a = 150 \, \mu\text{m} \) and \( d = 250 \, \mu\text{m} \), and \( h \) could vary between 140 and 635 µm. (b) The experimentally measured and numerically simulated waveguide transmission spectra for a 5-cm-long linear waveguide that consisted of periodically spaced rectangular blind holes with a depth of \( h = 635 \, \mu\text{m} \). The simulations assumed that the metal could be approximated either as a perfect conductor or as a metal with dielectric properties of stainless steel given in [50]. Reprinted with permission from [55]. Copyright 2011, IOP Publishing & Deutsche Physikalische Gesellschaft. CC BY-NC-SA.
with the fact that the individual apertures are fabricated via laser ablation, so small hole-to-hole variations are likely to cause further linewidth broadening.

The smaller than predicted dielectric values for metals have significant consequences for the field of THz plasmonics. At the very least, it suggests that analyses based on a perfect conductor approximation can only yield qualitative results, since loss is neglected at the outset. An ad hoc approach of introducing loss after the analysis may partially mitigate the issue in a few cases, but is more often likely to give erroneous results. This is particularly true if one considers a significant benefit of plasmonics – subwavelength focusing of radiation. At optical frequencies, it is possible to reduce the minimum spot size to below the diffraction limit, because of the dispersion properties of surface plasmons. Based on the Drude model (or a perfect conductor approximation), such demonstrations at THz frequencies should not be possible. However, there have been reports of subwavelength focusing based on tapered wires [61] and tapered parallel plate waveguides [62, 63]. Use of these recently obtained dielectric properties of metal in the THz spectral range may help explain the results. More generally, while it may not be possible to focus light as tightly as at optical frequencies, because SPPs are not as tightly bound to the interface, a new range of capabilities are likely nevertheless.

7. Conclusion

In summary, we have reviewed the measurements of the dielectric properties in the THz spectral range using a variety of free space and SPP-based measurement techniques. Interestingly, they yield dramatically different optical constants and, therefore, offer very different predictions concerning the interaction of THz radiation with metals. The free space measurements are largely consistent with the Drude model, while the SPP-based measurements are largely consistent with a broad range of SPP-based experimental implementations. The reason for this discrepancy is unclear, but it points out a clear need for theoretical insight into the problem, as well as further measurements. Indeed, it may be possible that existing theories can be adapted to shed light on this issue [64]. Aside from these issues, of course, the consistency of the SPP-based observations suggests that an entirely new range of THz plasmonic phenomena and device implementations are possible that may not have previously been considered.

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References

[1] E.D. Palik, *Handbook of Optical Constants of Solids*, Academic Press, New York, 1998.
[2] K.M. McPeek, S.V. Jayanti, S.J.P. Kress, S. Meyer, S. Iotti, A. Rossinelli and D.J. Norris, ACS Photonics 2 (2015) p.326–333.
[3] P.K. Gogna and K.L. Chopra, Thin Solid Films 57 (1979) p.299–302.
[4] R.L. Olmon, B. Slovick, T.W. Johnson, D. Shelton, S.-H. Oh, G.D. Boreman and M.B. Raschke, Phys. Rev. B 86 (2012) p.235147.
[5] A. Vašíček, J. Opt. Soc. Am. 37 (1947) p.145–153.
[6] L.G. Schulz, J. Opt. Soc. Am. 44 (1954) p.357–362.
[7] J.H. Weaver, E. Colavita, D.W. Lynch and R. Rosei, Phys. Rev. B, 19 (1979) p.3850–3856.
[8] P.B. Johnson and R.W. Christy, Phys. Rev. B 6 (1972) p.4370–4379.
[9] P.B. Johnson and R.W. Christy, Phys. Rev. B 9 (1974) p.5056–5070.
[10] H.-J. Hagemann, W. Gudat and C. Kunz, J. Opt. Soc. Am. 65 (1975) p.742–744.
[11] G. Brändli and A.J. Sievers, Phys. Rev. B 5 (1972) p.3550–3557.
[12] M.A. Ordal, L.L. Long, R.J. Bell, S.E. Bell, R.R. Bell, R.W. Alexander and C.A. Ward, Appl. Opt. 22 (1983) p.1099–1119.
[13] D.H. Auston and K.P. Cheung, J. Opt. Soc. Am. B 2 (1985) p.606–612.
[14] H. Yasuda and I. Hosako, Jpn. J. Appl. Phys. 47 (2008) p.1632–1634.
[15] D. Zhou, E.P.J. Parrott, D.J. Paul and J.A. Zeitler, J. Appl. Phys. 104 (2008) p.053110.
[16] W.-E. Sun, X.-K. Wang and Y. Zhang, Chin. Phys. Lett. 26 (2009) p.114210.
[17] F.-Y. Ma, J.-P. Su, Q.-X. Gong, J. Yang, Y.-L. Du, M.-T. Guo and B. Yuan, Chin. Phys. Lett. 28 (2011) p.097803.
[18] N. Laman and D. Grischkowsky, Appl. Phys. Lett. 93 (2008) p.051105.
[19] E. Ozbay, Science 311 (2006) p.189–193.
[20] J.A. Schuller, E.S. Barnard, W. Cai, Y.C. Jun, J.S. White and M.L. Brongersma, Nat. Mater. 9 (2010) p.193–204.
[21] M. Kaupinen and A.V. Zayats, Nat. Photonics 6 (2012) p.737–748.
[22] H. Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*, Springer-Verlag, Berlin, 1988.
[23] J.B. Pendry, L. Martin-Moreno and F.J. García-Vidal, Science 305 (2004) p.847–848.
[24] F.J. García-Vidal, L. Martin-Moreno and J.B. Pendry, J. Opt. A: Pure Appl. Opt. 7 (2005) p.S97–S101.
[25] K. Song and P. Mazumder, IEEE Trans. Electron Devices 56 (2009) p.2792–2799.
[26] M. Navarro-Cia, M. Beruete, S. Agrafoth, F. Falcone, M. Sorolla and S.A. Maier, Opt. Express 17 (2009) p.18184–18195.
[27] N. Yu, Q.J. Wang, M.A. Kats, J.A. Fan, S.P. Khanna, L. Li, A.G. Davies, E.H. Linfield and F. Capasso, Nat. Mater. 9 (2010) p.730–735.
[28] D. Martin-Cano, O. Quevedo-Teruel, E. Moreno, L. Martin-Moreno and F.J. García-Vidal, Opt. Lett. 36 (2011) p.4635–4637.
[29] E. Stone and E. Hendry, Phys. Rev. B 84 (2011) p.035418.
[30] F. Miyamaru, M. Kamijyo, N. Hanaoka and M.W. Takeda, Appl. Phys. Lett. 100 (2012) p.081112.
[31] Y. Nakata, T. Okada, T. Nakanishi and M. Kitano, Phys. Rev. B 85 (2012) p.205128.
[32] B. Ng, J. Wu, S.M. Hanham, A.I. Fernández-Domínguez, N. Klein, Y.F. Liew, M.B.H. Breese, M. Hong and S.A. Maier, Adv. Opt. Mater. 1 (2013) p.543–548.
[33] T.J. Cui and X. Shen, Terahertz Sci. Technol. 6 (2013) p.147–164.
[34] Z. Yu, Z. Gao, Z. Song and Z. Wang, Appl. Opt. 53 (2014) p.1118–1123.
[35] Y.J. Zhou, Q.X. Xiao and B. Jia Yang, Sci. Rep. 5 (2015) p.14819.
[36] A. Agrawal, Z.V. Vardeny and A. Nahata, Opt. Express 16 (2008) p.9601–9613.
[37] K. Wang and D.M. Mittleman, Nature 432 (2004) p.376–379.
[38] A. Sommerfeld, *Electrodynamics*, Academic Press, New York, 1952.
[39] G. Goubau, J. Appl. Phys. 21 (1950) p.1119–1128.
[40] F.L. Wentworth, J.C. Wiltse and F. Sobel, IEEE Trans. Microwave Theory Tech. 9 (1961) p.512–518.
[41] G. Goubau, Proc. IRE 39 (1951) p.619–624.
[42] N.C.J. van der Valk and P.C.M. Planken, Appl. Phys. Lett. 87 (2005) p.071106.
[43] L.S. Mukina, M.M. Nazarov and A.P. Shkurinov, Surf. Sci. 600 (2006) p.4771–4776.
[44] T.-I. Jeon and D. Grischkowsky, Appl. Phys. Lett. 88 (2006) p.061113.
[45] K. Wang and D.M. Mittleman, Phys. Rev. Lett. 96 (2006) p.157401.
[46] A. Agrawal and A. Nahata, Opt. Express 15 (2007) p.9022–9028.
[47] J.A. Deibel, K. Wang, M. Escarra, N. Berndsen and D.M. Mittleman, C.R. Phys. 9 (2008) p.215–231.
[48] W. Zhu, A. Agrawal, H. Cao and A. Nahata, Opt. Express 16 (2008) p.8433–8439.
[49] M. Gong, T.I. Jeon, D. Grischkowsky and Others, Opt. Express 17 (2009) p.17088–17101.
[50] V.V. Gerasimov, B.A. Knyazev, A.K. Nikitin and G.N. Zhizhin, Appl. Phys. Lett. 98 (2011) p.171912.
[51] S. Pandey, S. Liu, B. Gupta and A. Nahata, Photonics Res. 1 (2013) p.148–153.
[52] V.V. Gerasimov, B.A. Knyazev, I.A. Kotelnikov, A.K. Nikitin, V.S. Cherkassky, G.N. Kulipanov and G.N. Zhizhin, J. Opt. Soc. Am. B 30 (2013) p.2182–2190.
[53] M.M. Nazarov, A.P. Shkurinov, F. Garet and J.-L. Coutaz, IEEE Trans. Terahertz Sci. Technol. 5 (2015) p.680–686.
[54] W. Zhu, A. Agrawal and A. Nahata, Opt. Express 16 (2008) p.6216–6226.
[55] G. Kumar, S. Pandey, A. Cui and A. Nahata, New J. Phys. 13 (2011) p.033024.
[56] V. Astley, J. Scheiman, R. Mendis and D.M. Mittleman, Opt. Lett. 35 (2010) p.553–555.
[57] A. Nahata and W. Zhu, Opt. Express 15 (2007) p.5616–5624.
[58] J. Gómez Rivas, C. Schotsch, P. Haring Bolivar and H. Kurz, Phys. Rev. B 68 (2003) p.201306.
[59] J. Gómez Rivas, C. Janke, P. Bolivar and H. Kurz, Opt. Express 13 (2005) p.847–859.
[60] E. Hendry, M. Lockyear, J. Gómez Rivas, L. Kuipers and M. Bonn, Phys. Rev. B 75 (2007) p.235305.
[61] V. Astley, R. Mendis and D.M. Mittleman, Appl. Phys. Lett. 95 (2009) p.031104.
[62] H. Zhan, R. Mendis and D.M. Mittleman, Opt. Express 18 (2010) p.9643–9650.
[63] S. Liu, O. Mitrofanov and A. Nahata, Opt. Express 24 (2016) p.2728–2736.
[64] J. Lloyd-Hughes and T.-I. Jeon, J. Infrared Millim. Terahertz Waves 33 (2012) p.871–925.