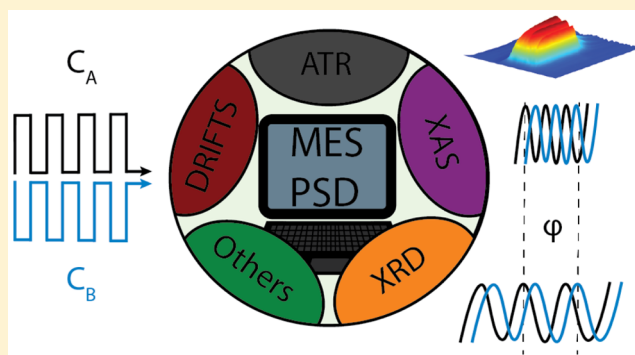


Applications of Modulation Excitation Spectroscopy in Heterogeneous Catalysis

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ABSTRACT: *In situ* and *operando* spectroscopic techniques are crucial for our understanding of complex heterogeneously catalyzed reactions. Under actual reaction conditions, however, many phenomena such as adsorption, (by)-product formation, and desorption of various species in different phases occur simultaneously, leading to crowded spectra that are difficult to interpret. About 15 years ago, modulation excitation spectroscopy (MES) was introduced to the heterogeneous catalysis community and has been increasingly applied since then. The periodic perturbation of a given system, in combination with phase-sensitive detection (PSD) analysis, significantly reduces noise, distinguishes between active and spectator species, and enables extraction of kinetic information. In this review article, we discuss the origin and theory of MES, summarize different application examples (with an emphasis on heterogeneous catalysis), and suggest future developments of the technique.



INTRODUCTION

One of the great challenges for the *in situ* characterization of catalysts is the fact that, most often, the active sites are only present in small quantities. Hence, it is important to use highly sensitive spectroscopic tools, including sophisticated data treatments, to extract the most information possible from catalyst surfaces. Furthermore, especially in heterogeneous catalysis, many different phenomena such as adsorption, (by)-product formation, and desorption are spectroscopically superimposed and occur simultaneously, which makes spectra interpretation highly challenging. It was in the year 2001, when Baurecht and Fringeli¹ introduced a novel methodology called modulation excitation spectroscopy (MES) that added such a highly sensitive and selective method to the toolbox of *in situ* and *operando* spectroscopic techniques that was found to be especially valuable for the analysis of heterogeneous catalysts. As shown in Figure 1, since 2001, the number of articles using or discussing MES has been increasing. Initially, attenuated total reflection infrared spectroscopy (ATR-IR) was the spectroscopic technique of choice; however, more recently, other techniques such as polarization–modulation infrared reflection absorption spectroscopy (PM-IRRAS), diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS), X-ray absorption spectroscopy (XAS), X-ray diffraction (XRD), and combinations of these techniques and others have been used in conjunction with MES as well. Any time-resolved spectroscopic technique can, in principle, be combined with MES.^{2,3} When choosing a specific technique, there are certain limitations, in terms of time resolution of the spectrometer and kinetics of the studied systems, that must be considered. To be able to capture dynamic processes, the sampling rate of time-

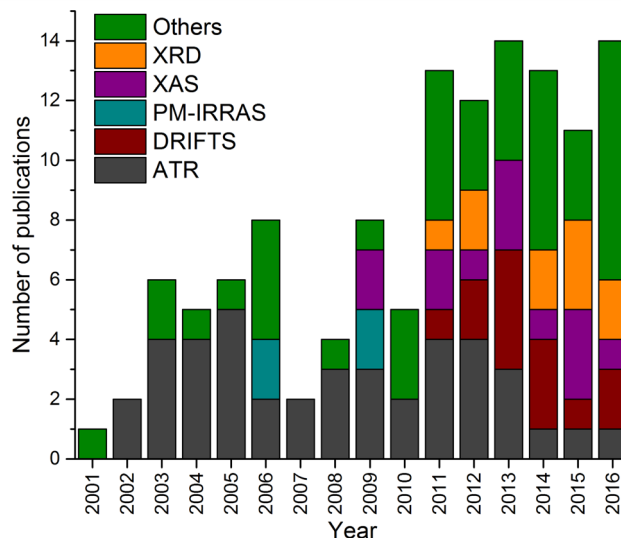


Figure 1. Development of the number of modulation excitation spectroscopy (MES) articles published in the last 15 years (list might be incomplete). Others include, imaging, combinations of techniques, accessories for MES, theoretical development, and reviews.

resolved spectra must be ~ 1 order of magnitude greater than the modulation frequency, which itself should be chosen in a

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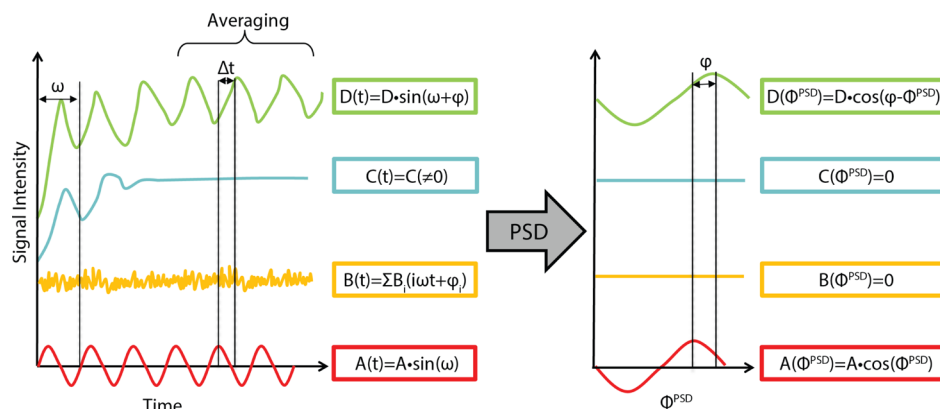


Figure 2. Schematic illustration of the working principle of PSD. $A(t)$ is the stimulation function, $B(t)$ is noise, $C(t)$ is a response of a spectator species, and $D(t)$ is the response of an active species. The stimulation function is, in this case, a sine wave with frequency ω . Demodulation using PSD transforms time-domain spectra to the phase domain. Instead of being time-dependent, the spectra are now a function of the phase angle Φ^{PSD} . Instead of appearing at a certain time delay Δt , in the phase domain, the absolute phase delay φ contains information about the dynamics and kinetics of the studied system.

similar range to the relaxation times of the studied system. For instance, FT-IR spectrometers can easily acquire several spectra per second, thanks to the use of the rapid scan mode, which means that the monitored transient processes in the studied system should not be complete within <10 s. For even faster kinetics, the step scan mode can be used in which time resolutions in the range of a few nanoseconds can be achieved.^{4,5} Thus, a suitable spectroscopic technique must be chosen, depending on the studied materials and the kinetics of the studied catalytic processes.

In this article, we review the origin and the theory behind MES, we give an overview on different applications focusing on heterogeneous catalysis, and, finally, we give an outlook on possible future directions.

■ ORIGIN OF MES AND THEORY

While it is true that the contribution by Baurecht and Fringeli in 2001¹ was the one that sparked the use of MES for applications in heterogeneous catalysis, it was much earlier that scientists developed similar ideas for other applications. For instance, Hexter⁶ suggested a procedure for MES as a technique to obtain vibrational spectra of excited electronic states by modulating UV–vis light and recording the transient behavior of IR vibrations. Others took up the idea, further developed the technique, designed new spectrometer arrangements, and applied it to various systems.^{7–14} In the late 1990s, first works on heterogeneously catalyzed reactions, where concentration modulation was applied to get insights into the reaction mechanisms, were published.^{15–18}

However, in these early works, the demodulation or phase-sensitive detection (PSD) that transforms spectra from the time domain to the phase domain and leads to some advantageous properties that will be discussed in detail below, was performed during data collection. This led to significant challenges associated with the general applicability of the technique. For instance, step-scan spectrometers were required, phase corrections for the fast Fourier transformation were more complicated, and additional lock-in amplifiers, data acquisition channels, electronics, and special software were needed. Vector-based PSD as described by Baurecht and Fringeli¹ eliminated most of these challenges and allowed for a convenient offline demodulation after the acquisition of time-resolved spectra.

The working principle of MES is similar to a digital lock-in amplifier, where a weak signal must be filtered out of a noisy background, as represented in Figure 2. The chosen type and frequency of stimulation ($A(t)$) are crucial to obtain high-quality spectra. In most of the applications that are discussed in the next sections, concentration modulation, i.e., the periodic change of the concentration of a certain species, was used. Other possibilities are a modulation of the sample temperature, pressure, pH, light flux, electric potential, and isotopic labels, among others. A prerequisite of MES is that the studied process is reversible or quasi-reversible within the time frame of one modulation period and that the system does not significantly deactivate throughout the experiment. During this modulation, the spectrometer is continuously acquiring spectra and hence records the response of the studied system to the chosen stimulation. Different species will respond differently to the stimulation.¹⁹ As shown in Figure 2, noise $B(t)$ is not affected by the stimulation and occurs randomly while the spectator species $C(t)$ (i.e., species that are not directly involved in the mechanism, e.g., from the catalyst support or species that adsorb to the surface and do not react further, might follow the stimulation initially and then reach a steady signal. Finally, the species that we are most interested in, i.e., active species $D(t)$ that are perturbed by the stimulation, follow the stimulation with the same frequency but with a certain time delay Δt . Note that the time-resolved spectra that are actually measured at each spectral position i , $E_i(t)$, are a linear combination of contributions from $B(t)$, $C(t)$, and $D(t)$:

$$E_i(t) = b_i \cdot B_i(t) + c_i \cdot C_i(t) + d_i \cdot D_i(t)$$

Once the system reaches a quasi-steady state (usually after few modulation periods), several modulation periods are averaged to further enhance the signal-to-noise ratio. The subtraction of the background spectrum, i.e., the first spectrum of the averaged period, further filters out unwanted signals, which is especially important for solid–liquid reactions, where the solvent and liquid-phase components absorb a lot of infrared radiation and might mask the signals from active species. The mathematical treatment (PSD) then is applied on the averaged spectra to transform them from the time domain to the phase domain, according to the following equation:

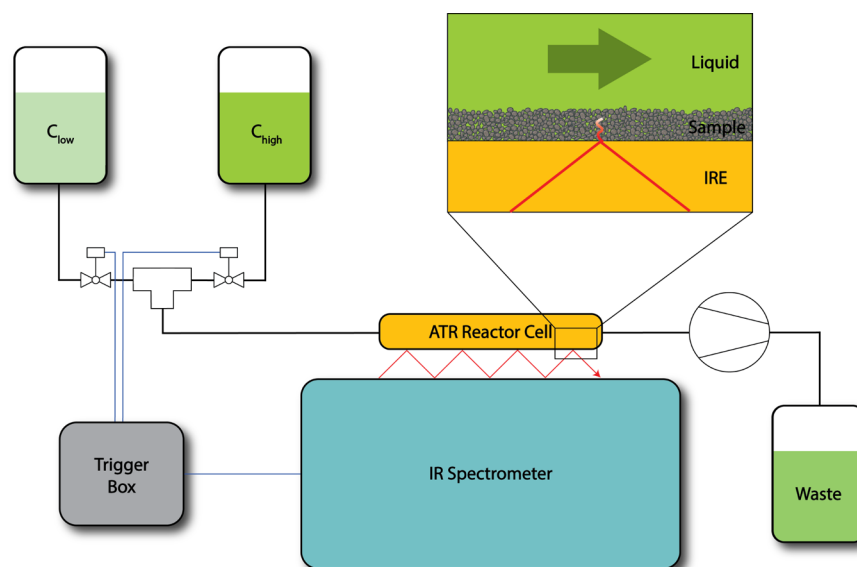


Figure 3. Schematic illustration of a concentration-modulation ATR-IR setup. Two tanks are connected to the ATR cell through electronically actuated valves that are triggered by the spectrometer. At the outlet, a peristaltic pump pulls the liquids over a thin catalyst layer (μm range) that is deposited on the ATR crystal.

$$E_{i,k}(\phi_k^{\text{PSD}}) = \frac{2}{T} \int_0^T E_i(t) \sin(k\omega t + \phi_k^{\text{PSD}}) dt \quad (1)$$

where T is the length of one period, ω is the modulation frequency, k is the demodulation index, ϕ_k^{PSD} is the phase angle for demodulation k , and $E_i(t)$ and $E_{i,k}(\phi_k^{\text{PSD}})$ are the response at spectral position i in the time domain and phase domain. Only the signals that follow the fundamental frequency ω or a multiple of it (harmonics) will show up significantly in the phase domain, allowing for discrimination between active and spectator species. However, there are also exceptions to this general rule, if, for instance, spectator species follow similar or faster kinetics than active species, this discrimination is not possible. As an example in heterogeneous hydrogenations over supported noble metals, the reactants might adsorb to the support and show similar kinetics than active species but are catalytically inactive.²⁰ The signal-to-noise ratio gets further enhanced, as any noise that is not affected by the stimulation gets eliminated. Another advantage of the PSD analysis is that the absolute phase delay φ , i.e., the difference in phase between the modulation function $A(\phi_k^{\text{PSD}})$ and one specific spectral position $E_{i,k}(\phi_k^{\text{PSD}})$ is well-defined, which is not always the case in transient time-resolved experiments. Furthermore, φ can be used for the microkinetic analysis of the studied processes. In the case of a two-step reaction $A \rightarrow B \rightarrow C$, for instance, the characteristic signals of the different species will have maximum amplitudes according to $\phi_A^{\text{PSD}} < \phi_B^{\text{PSD}} < \phi_C^{\text{PSD}}$. Hence, a thorough analysis allows for kinetic differentiation of pathways and lifetimes of active species during the modulation period. This kinetic differentiation also allows for distinguishing between heavily overlapping peaks, as long as they exhibit different kinetics during the modulation. Ultimately, the phase-domain analysis could be used to yield quantitative kinetic information such as rate constants from the amplitudes and phase delays after back-transformation to the time domain. However, so far, mostly qualitative or semiquantitative analyses have been performed. Even though the mathematical framework of MES and PSD is based on sine-wave stimulation, in practice, especially for concentration modulations, square-wave

modulations are more commonly used. The reason for this is the much simpler setup, where basically only two valves need to be switched on and off repeatedly and no steady concentration change is required.²¹ Since a square wave can be mathematically written as a sum of sine waves with odd frequencies, the response to a square-wave stimulation is hence the sum of the responses to the stimulation of each of the $(2n - 1)\omega$ frequency components.²² By setting $k = 2n - 1$, it would be possible to separately extract the different $(2n - 1)\omega$ frequency components with just one experiment, whereas $2n - 1$ sine-wave stimulation experiments would be needed to obtain the same information. A nonlinear response to the perturbation leads to significant contributions of higher-order harmonics ($k > 1$). An example in chemical kinetics would be a reaction step that does not follow first-order kinetics. Most often, however, only the fundamental frequency ($k = 1$) is analyzed.

■ MES APPLICATIONS

Attenuated Total Reflection Infrared Spectroscopy. As mentioned above, the first applications of MES to study solid/liquid interfaces were predominantly conducted using ATR-IR spectroscopy. The main advantages of using ATR-IR, compared to other infrared techniques, are the close contact of the catalyst with the internal reflection element (IRE) and the several reflections along the catalyst bed that significantly increase the sensitivity.^{23–27} As shown in Figure 3, the evanescent wave emerging at the boundary between the sample (low refractive index) and the IRE (high refractive index) penetrates ca. $1\text{--}2\ \mu\text{m}$ into the sample and, hence, probes the solid/liquid interface with high sensitivity. The penetration depth is wavelength-dependent and is determined by the ratio of refractive indices of the sample and the IRE. Commonly used IRE crystals are made of ZnSe, germanium, silicon, or diamond and they are chosen based on their optical properties as well as the chemical compatibility. Typically, the catalyst is deposited onto the IRE by letting the solvent of a slurry evaporate, leaving a thin catalyst layer on the IRE. To get a mechanically stable layer, it is important to use small catalyst

particles, to sonicate the slurry before applying it and to choose an appropriate evaporation temperature. However, depending on the type of catalyst, the polarity of the solvent, and the chosen flow rate, the catalyst layer might still be washed off over time, limiting the possible operational conditions of such ATR experiments. Figure 3 also shows a common setup for concentration–modulation for studying solid/liquid interfaces with ATR-IR. Two tanks, one filled with a low concentration (C_{low}) and one filled with a high concentration (C_{high}), are connected via two electronically activated valves to the ATR cell in the IR spectrometer. An accurate synchronization between spectra acquisition and switching of the valves is ensured through a trigger box that sends an electronic signal to the valves once the measurement starts. In order to get a fast exchange of the liquids, the dead volume between the valves and within the cell must be kept as small as possible. A volume of $<100\ \mu\text{L}$ is typically required to get fast exchange and diffusion at typically used MES frequencies (1–100 mHz for ATR).²¹ In addition, it is advisable to use small-diameter tubing to further reduce the dead volume, as well as being aware of the operational limits, with regard to heat and mass transport of the used ATR accessories.^{28,29} In terms of liquid pumps, two different options have been applied. Either the liquids are pushed through the ATR accessory, for instance with an HPLC or syringe pump, or, more commonly, the liquids are pulled through with a peristaltic pump. The latter has the advantages that it is relatively inexpensive and easy to implement with the electronically controlled valves shown in Figure 3. Most accessories can also be heated to reaction temperatures and some can be operated at elevated pressures.

In their publication from 2001,¹ Baurecht and Fringeli used an example of pH modulation with an arachidic acid bilayer to show the benefits of MES. In a follow-up study, they investigated folding and unfolding dynamics of RNase A using temperature modulation with ATR.³⁰ This type of stimulation has not been applied very often since then, probably because of technical difficulties associated with fast heat exchange and temperature control in ATR accessories. The temperature amplitude was $\sim 10\ ^\circ\text{C}$, with a mean temperature of $63\ ^\circ\text{C}$, which is roughly the melting point of RNase A. Although the aim of that work was to show the applicability of PSD and to obtain high quality phase-resolved spectra, details about the conformation of different functional groups and amino acids were also obtained. In the following years, additional reports studying biochemical applications were published,^{31–37} but the focus of MES-ATR shifted more toward applications in heterogeneous catalysis, where concentration–modulation was often applied. In particular, adsorptions, oxidations, and (asymmetric) hydrogenations have been studied. Baiker and co-workers used ATR-MES to probe chiral recognition in liquid chromatography.^{38,39} To do so, they immobilized chiral selector units on porous silica particles that were deposited onto the IRE. It was shown that a specific hydrogen-bonding interaction between the immobilized selector and only one of the two enantiomers forms, which ultimately leads to the desired separation. A later study used a commercially available chiral stationary phase deposited on the IRE and came to similar conclusions.⁴⁰ Bürgi and co-workers used ATR-MES to study self-assembled monolayers (SAM) of chiral amino acids and short-chain peptides on gold surfaces.^{41–48} Such SAMs have the potential for sensing and specific recognition of certain organic molecules. Since the formation of an SAM can take up to 2 h, this process is usually

monitored using standard time-resolved techniques without MES. However, to get a fundamental understanding, for instance, of the interaction with other molecules or the influence of the pH on the SAMs, MES can be efficiently used. To perform these experiments, an IRE was coated with a thin film of gold onto which the SAM was formed. MES proved to be a valuable tool in such applications, revealing details about different adsorption modes, enantiodiscrimination, and differences between chemisorbed and physisorbed layers. Other examples of adsorption studies include the adsorption of BINAP (2,2'-bis(diphenylphosphino)-1,1'-binaphthyl) to Pd⁴⁹ or the interaction of cholate with immobilized human serum albumin.⁵⁰

In the field of oxidations, early work was done on epoxidations over titania–silica catalysts.^{51,52} The example in Figure 4, where the cyclohexene concentration was modulated

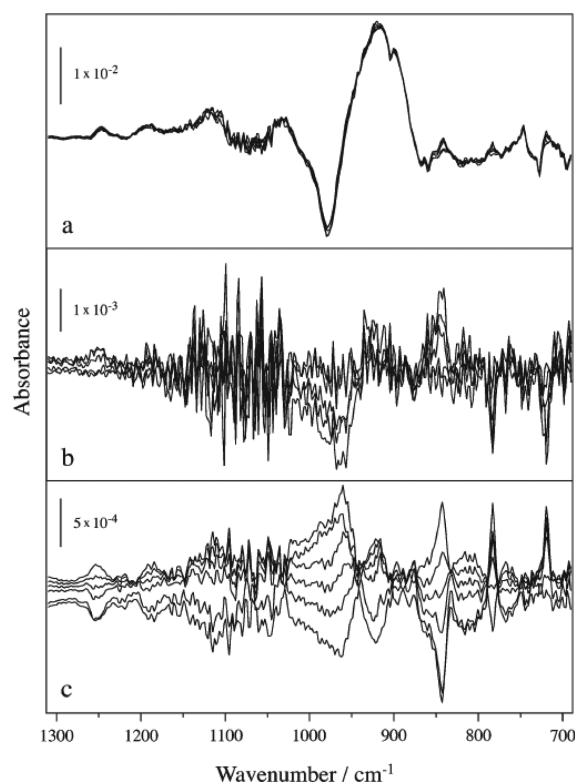


Figure 4. ATR spectra for epoxidation experiment recorded under forced modulation of the cyclohexene concentration: (a) time-resolved absorbance spectra, (b) difference spectra (obtained by just subtracting one arbitrary spectrum), and (c) phase-domain spectra after PSD of the spectra in panel (a). (Reproduced with permission from ref 51. Copyright 2003, Royal Society of Chemistry, London.)

at constant *tert*-butyl hydroperoxide concentration, demonstrates how the application of PSD increases the signal-to-noise-ratio and makes it easier to identify spectral features. In a standard transient experiment with background subtraction (b), most of the features are not discernible. Other studies looked at aerobic oxidations of cyclic alcohols, where the tanks in Figure 3 are saturated with the desired gases, i.e., bubbling an inert gas through C_{low} and air through C_{high} .^{53–55} A highly cited publication used modulation experiments with CO_2 -saturated toluene to probe the basic properties of the supported gold catalyst.⁵⁶ Using MES, distinct differences compared to transient adsorption experiments were found, and it was

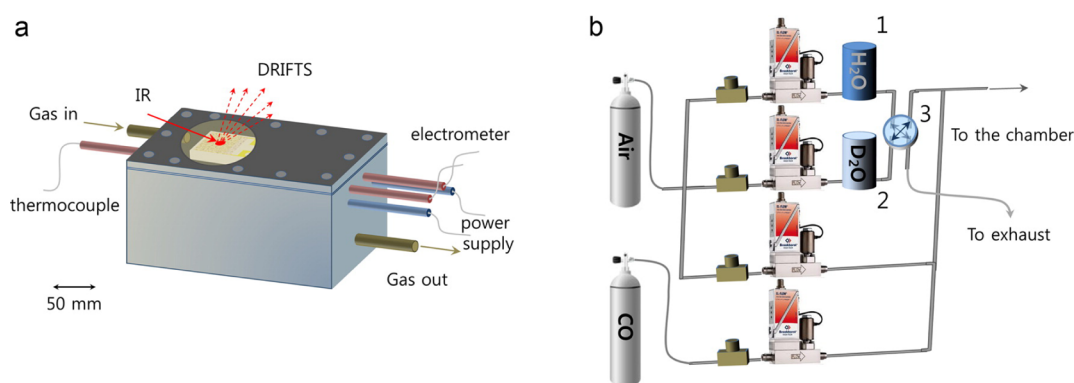


Figure 5. (a) Environmental chamber for operando DRIFTS and resistance measurements, and (b) gas-mixing system to perform H₂O/D₂O exchange in the presence of CO. (Reproduced with permission from ref 84. Copyright 2014, American Chemical Society, Washington, DC.)

concluded that some of the signals that were visible in the transient experiments were actually originating from spectator species. In another example, the oxidation of 2-propanol over Pd/Al₂O₃ was studied.⁵⁷ In addition to the ATR cell, an ultraviolet-visible light (UV-vis) spectrometer was added to the outlet of the cell to measure the liquid phase online. This approach is well-suited for monitoring fast changes that occur at the solid/liquid interface. In that work, the authors found evidence for a 2-propoxide intermediate and proposed an oxidative dehydrogenation mechanism.

In asymmetric hydrogenations, weak hydrogen-bonding interactions between a chiral modifier and the prochiral substrate lead to enantioselective catalysis, similar to the discussed chiral separations.^{58,59} Hence, such reactions have been studied with ATR-MES as well. The example of cinchonidine (CD)-modified noble-metal surfaces is probably the system that has been studied most with MES. In the enantioselective hydrogenation of a pyrone catalyzed by CD-modified Pd/TiO₂, MES was used to disentangle crowded spectra in the phase domain.⁶⁰ Carboxylate species were identified and appear to have a negative effect on enantioselection. In 2003, the first indications for weak N–H–O interactions between ketopantolactone and cinchonidine adsorbed on a Pt/Al₂O₃ catalyst were found using ATR-MES.⁶¹ More recently, the proposed interactions were refined, as an additional O–H–O interaction between CD and the substrate was found.^{62,63} Interactions with other substrates and additives were studied as well.^{20,64–70}

ATR-MES has also been applied to study photocatalytic systems,^{71,72} where a UV-light source was used for stimulation. Other monitored reaction systems include amine-functionalized silicas that catalyze Knoevenagel condensations⁷³ and heteropoly acids that catalyze decomposition reactions.⁷⁴

Recently, we have extended the use of MES-ATR to microporous and mesoporous materials, namely, porous stannosilicates.⁷⁵ The different pore structures of these materials lead to different spectroscopic features that allowed us to explain macroscopic observations and computational predictions on a molecular level. MES also helped in analyzing diffusion within these materials. It was found, for instance, that, for the microporous catalyst, the reaction product did not easily diffuse out of the catalyst pore and once it had left the pore, it did not re-enter, preventing further reactions and hence leading to higher selectivities.

Polarization–Modulation Infrared Spectroscopy. In another interesting application, an attempt was made to couple

MES with polarization–modulation infrared reflection absorption spectroscopy (PM-IRRAS).^{76,77} PM-IRRAS is a reflection infrared technique that is highly surface sensitive and is often applied for thin films. In standard PM-IRRAS measurements, the gas-phase contribution to the acquired spectrum is filtered out by taking the difference between the p- and s-polarized reflections over metallic surfaces. For heterogeneous catalysis under relevant pressure regimes, however, the gas-phase contribution can be used to simultaneously monitor reactions.

To study dynamic processes, PM-IRRAS was used, together with MES to get insights into CO oxidation over Pt. Also in this application, the signal-to-noise ratio was significantly increased and some new spectroscopic features could be observed besides the adsorbed CO.⁷⁶ The PM-IRRAS accessory that was used was especially designed for application with MES to have a small cell volume, excellent mixing properties and fast exchange of the gas phase. PM-IRRAS can also be applied for studying solid/liquid interfaces.⁷⁸ To do so, a CaF₂ prism was used atop the reflection element to achieve a liquid film thickness of ~10 μm.⁷⁹ For instance, the adsorption behavior of different acids on alumina was studied using this technique, together with MES.⁸⁰ It was found that dimer-like salicylic acid species formed through hydrogen bonding close to the alumina surface when increasing the concentration. Even though PM-IRRAS allows for the simultaneous monitoring of surface and bulk species for both gas- and liquid-phase reactions, there are only few examples of its use in conjunction with MES, likely because of the relatively high cost of a PM-IRRAS setup.

Diffuse Reflectance Infrared Spectroscopy. Besides PM-IRRAS, diffuse reflectance infrared spectroscopy (DRIFTS) is another technique that is well-suited for monitoring heterogeneously catalyzed gas-phase reactions. In DRIFTS, a powdered sample is placed in a sample cup where its rough surface creates diffuse reflections when infrared radiation is directed onto the sample. The main advantage of this technique is that no sample preparation is needed prior to the measurement, which, for instance, enables studying support effects of supported metals much more easily than with PM-IRRAS. Furthermore, the samples can be heated to high temperatures and subjected to elevated pressures to simulate reaction conditions for gas-phase reactions. On the other hand, the gas flow patterns and temperature distributions in DRIFTS accessories are not always optimal and the particle size/packing of the bed might influence the outcome of a measurement.^{81–83} Nevertheless, DRIFTS has been increasingly used, together with MES, to obtain insights into gas–solid interfaces under

reaction conditions. Figure 5 shows an example of a DRIFTS setup equipped for MES.⁸⁴ The chosen modulation in that specific example was a concentration modulation between H₂O and D₂O and was achieved by simply switching a four-way-valve (feature “3” in Figure 5). The DRIFTS cell itself should have a low dead volume to ensure fast exchange of the gas phase upon switching the valve.

The first MES study using DRIFTS was published in 2011.⁸⁵ A commercially available DRIFTS accessory was customized, replacing the conventional dome with a flat CaF₂ window to reduce some dead volume. In addition, a mass spectrometer was connected to the outlet to simultaneously monitor the gas-phase composition. The preferential oxidation of CO over Cu-CeO₂ catalysts was investigated using that setup. MES was very useful in this example as a strong carbonyl signal that was detected under steady-state reaction conditions was found not to participate in the oxidation reaction under transient oxygen conditions, suggesting it to be a signal from a spectator species. In addition, weak variations in intensity of vibrations associated with carbonate and formate species below 2000 cm⁻¹ could be distinguished, because of the increased signal-to-noise ratio in the phase domain, as shown in Figure 6. By running the same

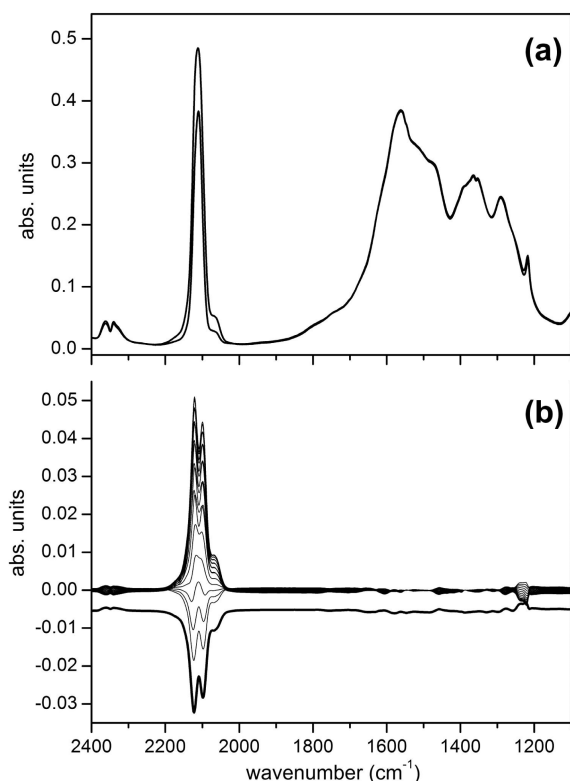


Figure 6. (a) Time- and (b) phase-resolved spectra during oxygen concentration modulation CO/H₂/O₂ vs CO/H₂ on Cu-CeO₂. A phase-resolved spectrum is offset to show the anticorrelation of gas-phase CO₂ and carbonyl species. (Reproduced with permission from ref 85. Copyright 2011, Elsevier, Amsterdam.)

experiment at 80 and 140 °C, it was found that two carbonyl vibrations responded differently to the temperature change, which helped them assign one of them (CO bound to slightly oxidized Cu) to be more readily oxidized than others.

In another study on CO hydrogenation over Pd using a similar setup, it was found that only a fraction of ~4% of the adsorbed CO molecules were reacting with hydrogen.⁸⁶ Also, in

this case, under steady-state conditions, mainly the unreactive species were probed while the more important reacting species were overshadowed, because of their low abundance. CO oxidation and related reactions have specifically benefitted from applying MES and PSD because of the existence of such spectator species.^{87–91} In a further example, isotope modulation was applied on the preferential oxidation of CO.⁹² By switching between a flow of H₂ and D₂, as well as between ¹²CO and ¹³CO, further insights into the reaction mechanism were obtained. For instance, water was found to be involved in the reaction pathway but not consumed. Also, the surface CO species were found to exchange much faster than formate or bicarbonate species, indicating a rather slow reaction of adsorbed CO and OH⁻ species. The most interesting aspect about isotope modulation is that the reaction is chemically under steady state, which is not the case for standard concentration-modulation, where the reaction is studied under quasi-steady state.

Collins and co-workers studied the adsorption of H₂ and CO₂ on a Pd/Ga₂O₃ catalyst using DRIFTS-MES.⁹³ Their study nicely demonstrates the kinetic differentiation of various carbonate species after applying PSD. Figure 7 shows the time-domain spectra (Figure 7a) and phase-domain spectra (Figure 7b), as well as a phase delay φ analysis. For instance, the band at 1660 cm⁻¹ attributed to monodentate-HCOO species shows a higher phase delay than the band at 1600/1580 cm⁻¹ attributed to bidentate-/bridged-HCOO and hence is more rapidly formed and decomposed to CO than the latter. The same research group also studied the role of oxygen vacancies in the water-gas-shift reaction on ceria-supported platinum catalysts.⁹⁴ It was found that monodentate-HCOO species and carboxylate species located at the metal support interface could be reaction intermediates, something that likely would have been overlooked with standard steady-state investigations.

In a similar approach, the H₂O/D₂O exchange was studied over SnO₂ materials in the presence of CO with the setup shown in Figure 5.⁸⁵ It was found that only traces of Cl in the material induce dramatic changes in water adsorption kinetics and the CO sensing mechanism. Also zeolites were studied using isotope MES in the catalytic methanol amination over sodium-exchanged mordenite.⁹⁵ In that study, methanol and deuterated methanol were modulated in the presence and absence of ammonia. It was found that, besides the well-known shape selectivity, other factors such as a hydrogen-bond network of methanol agglomerates also play an important role in this reaction.

Finally, we recently published a study using both concentration and isotope modulation in the production of 1,3-butadiene from ethanol over Ta-BEA zeolites.⁹⁶ We built a new setup that consists of two independent syringe pumps that deliver liquids into a heated spiral, where evaporation occurs. By adjusting the inert gas flow and the liquid flow rates, the gas-phase concentration can be conveniently controlled. In this particular example, the reaction pathway involves many reaction steps and intermediates, which makes a steady-state spectroscopic analysis challenging. Hence, switching between different combinations of reactants and intermediates in a modulated fashion can help disentangle the spectra. The gas-phase composition was simultaneously monitored with a mass spectrometer at the outlet of the DRIFTS cell. The information from the gas/solid interface and the gas phase was then analyzed together, to obtain a reaction mechanism of 1,3-butadiene production over Lewis acidic Ta-BEA.

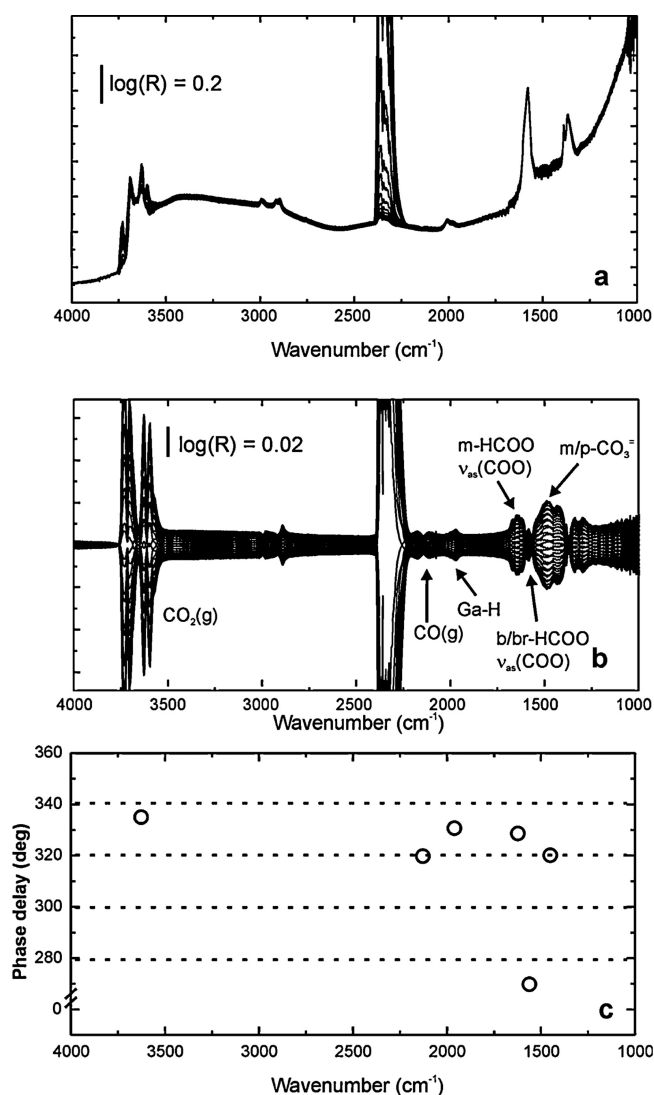


Figure 7. (a) Time-domain DRIFT spectra during concentration modulation with $\text{CO}_2/\text{H}_2\text{-Ar}$ over Ga_2O_3 (b) phase-domain spectra after PSD (c) phase delays (φ) for selected bands. Abbreviations: m-HCOO, monodentate; b-HCOO, bidentate; p-HCOO, polydentate; and br-HCOO, bridged carbonate. (Reproduced with permission from ref 93. Copyright 2013, Elsevier, Amsterdam.)

X-ray Absorption Spectroscopy. X-ray absorption spectroscopy (XAS) is another technique that has been frequently coupled with MES to obtain increased sensitivity. Because of the large penetration depth of X-rays, the obtained spectra are an average over many atomic structures within a specific sample. Most often, however, only a few atoms at the surface, e.g., of a metal nanoparticle, are actually of interest and may only be observed with highly sensitive techniques. Hence, the first *in situ* studies were performed during periodic operation, where some of them increased the sensitivity of the spectra by simply averaging over several modulation periods.^{97–99} The first step toward an analysis with PSD was reported in 2009, where the ignition behavior of noble-metal-catalyzed partial oxidation of methane was studied using quick-scanning extended X-ray absorption spectroscopy (QEXAFS).¹⁰⁰ QEXAFS allows for a fast data acquisition in the subsecond range under realistic *in situ* conditions. The application of MES on QEXAFS improves the signal-to-noise ratios without losing time or energy resolution, which makes this approach attractive

for relatively fast reactions.^{101–103} In that example, a principal component analysis (PCA) revealed two distinct regimes (heating and ignition) within the full modulation period.¹⁰⁰ Later, Ferri and co-workers published phase-resolved spectra of noble-metal catalysts during the catalytic oxidation of CO and the reduction of NO by CO.^{104–106} These studies showed the potential of MES for XAS as it drastically increased surface sensitivity and ultimately formed the basis to study working catalysts, even at low metal loading, that have been previously intractable for dynamic *in situ* studies. However, the usefulness of PSD for X-ray absorption spectra has also been questioned.¹⁰⁷ It was found that applying a low-pass filter yields spectra with similar signal-to-noise ratios, while no artifacts are introduced, which was not always the case with PSD. Indeed, the interpretation of EXAFS spectra in the phase domain is much more complex than in the case of vibrational spectroscopy.¹⁰⁸ As the EXAFS spectrum is essentially a combination of scattering properties that are not affected by the modulation experiment and structural properties that are affected by the modulation experiment, a systematic evaluation of the effect on the structural parameters needs to be done. Chiarello and Ferri resolved most of these issues in a combined simulation and experimental work with $\text{Pd}/\text{Al}_2\text{O}_3$ which provides some tools and guidelines to qualitatively and quantitatively understand phase-resolved EXAFS spectra.¹⁰⁹ For instance, the FT-phase-resolved spectrum can only be directly fitted if a shell completely appears and disappears during one modulation period. Besides these initial works and case studies, some additional applications of XAS with MES and PSD have been reported. For Pd incorporated in a perovskite structure, it was found that applying a periodic change in the feed composition for methane oxidation actually enhances the activity, compared to steady state.¹¹⁰ PSD analysis indicates that Pd reversibly leaves the perovskite framework, which influences catalytic activity. This highly active transient species most likely would not have been detected with conventional methods, again highlighting the usefulness of MES. An increased activity or selectivity in periodic operation is an effect that also has been observed for other catalytic processes.^{111–114} For such systems, XAS with MES and PSD is an outstanding tool, because, in that case, the information is obtained truly under reaction conditions. In an interesting application of MES, Nachtegaal and co-workers used a modulation that consisted of more than two discrete states, i.e., supported Ru particles were exposed to three different atmospheres: reducing (H_2 and CO), reducing and sulfiding (H_2 , CO, and H_2S), and oxidizing (O_2).¹¹⁵ The demodulated spectra of the entire modulation experiment is, in that case, simply the sum of the individual demodulated spectra of each square-wave function. At certain phase angles, some contributions will be zero, while others will not, which was used to conveniently analyze the data. Using this approach, they found that the formation of a Ru-sulfide phase was deactivating the catalyst.

Also, methane oxidation has been studied over supported Pd nanoparticles.¹¹⁶ Differences in the conversion between supports was most pronounced at the switches between oxidizing and reducing conditions. Those differences were attributed to different oxygen-storage capacities of the supports. Figure 8 shows the demodulated spectra of such an experiment over $\text{Pd}/\text{Al}_2\text{O}_3$. It is evident that the phase-domain spectra are significantly better resolved than the scaled difference spectrum (blue).

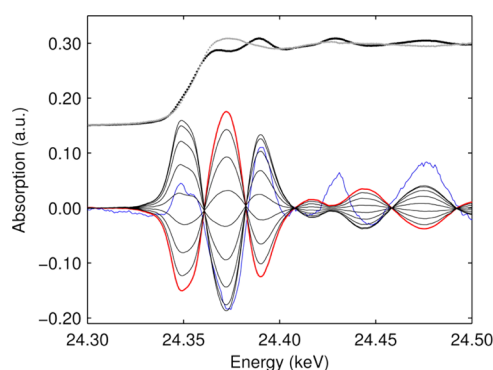


Figure 8. Demodulated spectra obtained from Pd/Al₂O₃ at 400 °C ($\phi_k^{\text{PSD}} = 0^\circ\text{--}160^\circ$), together with scaled spectra of Pd foil (black) and PdO powder (gray). The red spectrum corresponds to $\phi_k^{\text{PSD}} = 0^\circ$, and the blue spectrum is the scaled difference spectrum Pd_{foil}–PdO. (Reproduced with permission from ref 116, Copyright 2015, American Chemical Society, Washington, DC.)

More recently, X-ray emission spectroscopy has been used with MES and PSD.¹¹⁷ For instance, the redox behavior of Pt/Al₂O₃ and CO oxidation over Pt/CeO₂ were studied.^{118,119} In the latter case, a short-lived active Ce³⁺ species was found. In this material, the initial rate of ceria oxidation is at least 10 times higher than the rate of reduction, which is why these species cannot be observed under steady-state conditions. Interestingly, even under oxygen-rich conditions, the Ce³⁺ signal from the spectator species does not completely disappear, indicating that they are not involved in the catalytic cycle.

X-ray Diffraction, Combinations, and Others. Another evolving technique, in conjunction with MES, is X-ray diffraction (ME-XRD or MED).^{120–122} The idea here is to

periodically stimulate a crystal structure, where only a subset of atoms will change its properties.¹²³ The fundamental limitation of XRD is that it is based on an interference phenomenon and, therefore, the contribution of different subsets of atoms cannot be separated. This fact also does not allow for measuring the phase of the diffracted waves (the so-called phase problem of crystallography). MED can, in some cases, solve or at least greatly reduce these issues. Generally, there are two different problems that can be studied with MED. In the direct problem, structural information is recovered from MED intensities. In this case, it is assumed that a subset of atoms responds to the stimulation in a linear fashion in terms of structure amplitudes. This approach allows the separation of interferences from both silent and active atoms from the diffraction contribution of the active subset, something that is not possible with standard diffraction experiments. In the inverse problem, information about kinetics induced by the stimulation are studied. Here, it is assumed that the structural changes are known. This approach is suited for obtaining kinetic information on nonequilibrium systems *in situ*. Several examples will be discussed in this section; however, a more-detailed theoretical background of MED can be found in the literature.^{123–126}

As a first proof of principle, ZrO₂ powder has been studied using MED and different approaches to extract interferences have been tested.¹²⁷ Also, Pd supported on ceria–zirconia (Pd/CZ) has been characterized using MED and showed the detailed redox dynamics when exposed to a concentration modulation with CO and O₂.¹²⁸ Figure 9 shows time-resolved spectra as well as phase-resolved spectra of such an experiment. The change in oxidation state from metallic Pd(0) to Pd(II) oxide can be observed by the appearance and disappearance of the specific diffraction patterns.

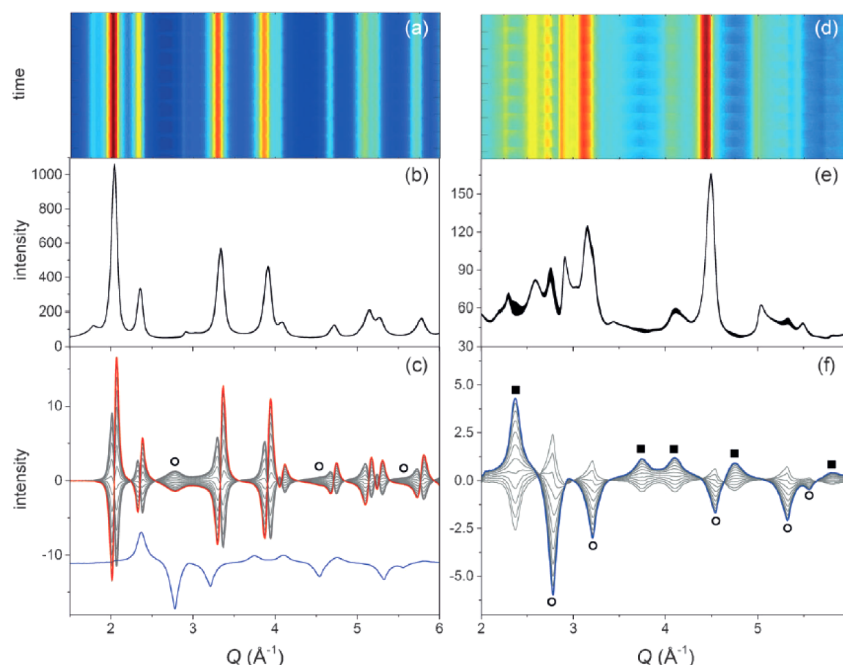


Figure 9. (a) Color map representation and (b) time-resolved hard XRD patterns for 2 wt % Pd/CZ during a full CO/O₂ modulation experiment at 573 K ($t = 50$ s). (c) Corresponding set of phase-resolved data ($\phi^{\text{PSD}} = 10^\circ\text{--}150^\circ$); the red profile is the in-phase pattern. The blue profile is the in-phase pattern obtained for 2 wt % Pd/Al₂O₃. (d)–(f) High-energy XRD data for an experiment with parameters identical to that performed with 2 wt % Pd/Al₂O₃ ($\phi^{\text{PSD}} = 70^\circ\text{--}180^\circ$). Symbol legend: (○) Pd, (■) PdO. (Reproduced with permission from ref 128, Copyright 2014, John Wiley and Sons, New York.)

This catalyst is particularly difficult to characterize with EXAFS, because of the small amount and size of Pd nanoparticles and the highly absorbing and scattering ceria in the sample. Some subtle changes induced by the modulation between CO and O₂ were greatly enhanced when applying PSD. Thus, MED provides an additional tool to characterize changes in the oxidation state of Pd.

In a promising application, Palin et al. studied the thermal behavior of xenon in a MFI zeolite.¹²⁹ By periodically exciting xenon inside the zeolite pores with a laser and subsequent mathematical treatment with PSD as well as principal component analysis (PCA), they managed to selectively probe the Xe atoms and filter out the contribution from the nonresponding zeolite. This method is particularly promising, because it could also be applied to light elements and molecules provided that the electron density of the light element can be modulated by an external stimulation.

Also, Raman spectroscopy can be used together with MES. In a combined MED and modulated Raman spectroscopic study, the structure of a spin crossover material was investigated using temperature modulation.^{130,131} It is technically challenging to perform temperature modulation as heating and cooling rates have to be equal in order to obtain a symmetric stimulation. Hence, the applied modulation frequencies are usually lower than, e.g., in concentration modulations. However, this also enables the use of spectroscopic techniques that do not have a particularly high temporal resolution, such as Raman spectroscopy. In the aforementioned example, the used modulation frequency was 0.5 mHz, which is an order of magnitude lower than in a typical MES-ATR experiment. Nevertheless, the authors found interesting details about their system such as a hysteresis loop that was much more pronounced in the XRD patterns than in the Raman spectra. This was attributed to the different sensitivities toward short- and long-range ordering of the two techniques. Finally, they attributed the crystallographic phase change triggered by the spin inversion to have a marked one-dimensional character, since it occurs through the elongation in one direction within the material. In another example, time-dependent surface-enhanced Raman spectra (SERS) of the surface plasmon resonance-mediated oxidation of *p*-aminothiophenol on Au/TiO₂ catalysts has been studied in a manner similar to MES.¹³² Only when the UV light was turned on, signals originating from the oxidation product started to appear due to charge transfer from UV-excited TiO₂ to Au. Because of the relatively low spectra acquisition time (ca. 5 s), this would be an example where Raman-MES could have been applied and further kinetic information and increased signal-to-noise ratio could be obtained.

Other examples of combinations of techniques are XRD-DRIFTS,^{133,134} XAS-DRIFTS,^{104,135,136} and DRIFTS-UV-vis.¹³⁷

MES can also be applied to other chemical systems. In an example by Jullien et al., the response of the pH to a periodic UV illumination of 2-hydroxyazobenzenes with a relatively high frequency (210 mHz) was studied.¹³⁸ By extracting the phase delay of the pH response, the authors were able to calculate rate constants for the trans-to-cis and the cis-to-trans isomerization. The same research group also built and refined the theoretical framework to apply MES on imaging techniques, which is especially promising for selective detection in mixtures of probes as well as heterogeneous systems.^{139–145} For instance, the brightness and the thermokinetic features of a probe are

often strongly dependent on its environment. Hence, in a multiphasic medium, e.g., a living cell, it is difficult to quantitatively analyze concentrations of probes of interest without prior knowledge of the probe location. Here, the out-of-phase first-order response in a modulation–excitation experiment can be used to get quantitative information on probes in a specific phase.

■ FUTURE DIRECTIONS/OUTLOOK

Even though the number of studies using modulation excitation spectroscopy (MES) has been growing recently, especially in heterogeneous catalysis, it is still not a widely used technique. It would certainly be unreasonable to apply MES on every reaction combined with every spectroscopic technique. However, when choosing the appropriate technique and experimental parameters for a given catalytic system, high-quality phase-resolved spectra can be obtained. The following conditions are important: (i) the studied reactions are reversible or pseudo-reversible, (ii) the time resolution of the chosen spectroscopic technique matches the kinetics of the reaction, (iii) no significant catalyst deactivation occurs over the period of one experiment, and (iv) mass transport limitations are avoided in order to get kinetically relevant information. However, when applied properly, MES can lead to information that might be overlooked with standard steady-state experiments and can lead to selective measurements with a high signal-to-noise ratio. One reason why it might not be used on a more regular basis may be the mathematical framework that must be implemented in order to perform the data analysis. Researchers from the Paul Scherrer Institute published their Matlab codes on their website, together with a tutorial on MES,¹⁴⁶ which should make it easier for other researchers to implement MES in their laboratories, including use with other spectroscopic techniques.

Another recent development, especially in heterogeneous catalysis, is the combination of several characterization techniques into one cell, as also briefly mentioned above.^{147,148} This approach allows for a simultaneous measurement of different catalyst properties. There have been some examples, where X-ray absorption spectroscopy (XAS) has been successfully combined with diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS), Raman spectroscopy, or ultraviolet-visible (UV-vis).^{135,149–151} In order to have a fast exchange of the gas or liquid phase, a low dead volume is required to obtain kinetically relevant information, especially using MES. This has been attempted by miniaturizing the reactors (e.g., using capillary reactors). However, geometrical constraints, especially for infrared cells, makes it challenging to combine all desired spectroscopic techniques into one cell. Hence, another approach could be to design a cell with a small dead volume that can be measured consequently instead of simultaneously with the different techniques, provided the catalyst does not deactivate over the time course of these measurements. It is also important to move toward more *operando* MES, meaning that the used cells should allow one to attain (heat and mass transport) conditions applied in the actual reactors, as well as simultaneously monitoring activity to be able to get reliable and transferable information.¹⁵² First steps into that direction have been made by routinely monitoring the gas-phase composition at the outlet of the reactor cells using online mass spectrometry. Reducing the dead volumes and optimizing the flow patterns can further lead to truly differential reactors that yield reliable kinetics. For

liquid-phase reactions that are still often performed under batch conditions, an attempt was made to use attenuated total reflection infrared spectroscopy (ATR-IR) with a recycle reactor to simulate batch conditions.¹⁵³ This approach further enables monitoring of the bulk liquid-phase composition, which can then be subtracted from the solid–liquid spectra, yielding true surface spectra. This reactor setup was already tested for MES applications and showed promising results. Well-designed experiments will allow the extraction of kinetic information that might not be accessible from conventional time-resolved spectra. In most of the described applications above, the discussion of the phase-domain data remains on a qualitative or semiquantitative level. Admittedly, this also is related to inherent limitations of the applied techniques. DRIFTS, for instance, is relatively difficult to quantify, because of the scattering nature of the reflected light. The same is true for ATR-IR, where slight changes of the refractive index of the sample lead to drastic changes in the penetration depth of the evanescent wave. Nevertheless, it would be ultimately desirable to be able to back-transform the highly smoothed phase-domain spectra into the time domain to get quantitative kinetic information. As briefly mentioned above, other data analysis concepts such as two-dimensional (2D) correlation spectroscopy,^{130,154} principal component analysis (PCA), or multivariate curve resolution (MCR) could be applied to analyze MES data.^{125,155} MCR allows for the extraction of information from large and complex time-resolved (modulated) datasets. It is a highly automated algorithm that allows one to efficiently process spectra and is a blind-source method, which might lead to easier access to highly sensitive spectra, in contrast to PSD.

In terms of applications, pressure modulation is a stimulation that has not been explored with MES so far.¹⁵⁶ A change in pressure can affect heterogeneous reactions in at least two ways.¹⁵⁷ For porous catalysts, pressure modulation can significantly increase transport within the pores or at the catalyst surface, especially for gas–solid and gas–liquid–solid reactions. Second, probably a rarer case, is that reactions that involve adjacent active sites or that are inhibited by a strongly adsorbing reactant or product may be sensitive to pressure changes. In some examples, pressure modulation did, indeed, lead to higher overall reaction rates. Such effects could be studied with MES, provided a setup periodically changing the pressure could be incorporated into an existing spectroscopic accessory. Generally, we believe that the number of applications of MES will keep increasing, especially for the discussed fairly new techniques (XRD, imaging) as well as other spectroscopic techniques. As shown with the many examples above, MES with PSD proves to be a versatile tool to obtain spectra with high signal-to-noise ratio, the possibility to distinguish between spectator, and active species, as well as an analysis of the dynamics of different species.

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Notes

The authors declare no competing financial interest.

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