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Experimental Noise Spectroscopy and the Measurement of Periodic Material Structures

P. Drexler, J. Seginak, J.Mikulka, D. Nešpor, M. Friedl, P. Marcoň, P. Fiala

Department of Theoretical and Experimental Electrical Engineering,
Technicka 12, 616 00 Brno, Czech Republic
Email: fialap@feec.vutbr.cz

Abstract. *The authors discuss the application of a broadband noise signal in the research of periodic structures and present the basic testing related to the described problem. Generally, noise spectroscopy tests are carried out to verify the behaviour of the response of periodic structures, and their objective consists in recording the properties of microscopic structures in natural and artificial materials. The aim is to find a metrological method utilizable for the investigation of structures and materials in the frequency range between 100 MHz and 10 GHz; this paper therefore characterizes the design of a suitable measuring technique based on noise spectroscopy and introduces the first tests conducted on a periodic structure. In this context, the applied equipment is also shown to complete the underlying theoretical analysis.*

Keywords: Nanomaterials; Periodic Structures; Noise; Noise Spectroscopy; Microscopic Structures.

1. Introduction

Sir Isaac Newton, the widely recognized founder of spectroscopy [1], discovered monochromatic light (Fig. 1) via an optical prism. The scientist later described his findings in Optics, one of the major works of science of all times; the first spectrometer was nevertheless presented only in 1860 by Kirchhoff and Bunsen. Generally, spectrometry can be defined as a discipline analyzing the properties and generation of the spectra of harmonic signals or electromagnetic waves. The related research methods are based on the interaction between an electromagnetic wave and the measured sample of matter. With respect to electromagnetic spectroscopy, it is vital to refer to the Raman technique, a tool providing information on the structure and spatial arrangement of the quantum mechanical model of a molecule. By extension, spectroscopy in its general sense is also applicable for different materials, such as carbon [2], [3]. The set of central subareas of the discussed field comprises spectroscopy utilizing nuclear magnetic resonance, which is applied to determine the distribution of atoms in the vicinity of nuclei exhibiting non-zero nuclear spin (1H, 13C, 31P, …). In the given context, let us note that nuclear magnetic resonance spectroscopy [4],[5],[6] is a physical-chemical method exploiting the interaction between atomic nuclei of the quantum mechanical model of matter and the external magnetic field. The technique examines the distribution of nuclear spin energies in the magnetic field and investigates the transition between individual spin states caused by radio frequency radiation. Considering noise spectroscopy, we can point out that this method is effectively practiced via both harmonic analysis and statistics. To evaluate the signals in continuous time, it is possible to use suitably the Fourier transform approach [7], which can be further modified for other signal types. The evaluation of discrete signals is then feasible by means of the discrete Fourier transform [8] and the fast Fourier transform algorithms [9]. However, the Fourier transform is not applicable for the investigation of non-stationary signals.

Periodic structures

From the perspective of description, a macroscopic material (MM) can be defined via a quantum mechanical (QM) model. The MM is then examined based on the incidence/radiation of an electromagnetic wave, and from this interaction we then deduce the properties of the sample. The QM model of the sample comprises a high number of repeated structures, and it is thus possible to use the term periodic material structure. Depending on the result of the EMG wave interaction, we can determine the basic and complementary properties of the sample (conductor; semiconductor; or insulator). Such utilization of similar effects is also typical of various subareas of spectroscopy [2]. Research in the given area was already performed by Yablonovitch, but his experiments focused on an EMG wave in the spectrum of light [10]. The first phases of research into the interaction between radiation and a periodic structure can be traced back to the initial years of the 20th century, a period when Bragg discovered by observation that, under certain conditions, atomic structure can behave like a mirror. This holds true, for example, in X-rays if we have the wavelength λ and distance *d* between two neighbouring atoms at the angle of incidence Θ:

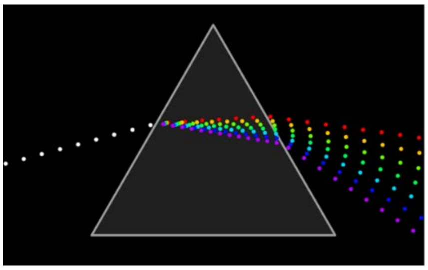


Fig. 1. A prism showing the decomposition of light.

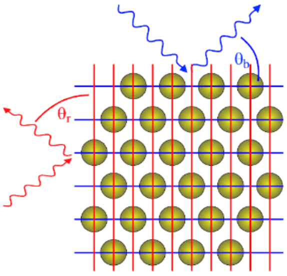


Fig. 2 X-ray reflection from a periodic structure of atoms.

$$\lambda = 2d \cdot sin(\Theta \pm \delta), \qquad (1)$$

where δ is the angle deviation. Reflections of the incident EMG wave will occur, Fig. 2. It is nevertheless obvious that the material and its atoms as such do not exhibit the above-indicated property, and we also need to ensure periodicity of the structure on the scale of wavelengths of the incident EMG wave. In periodic structures, the described effect can be used to determine the properties of the monitored sample of material. If an unknown sample of material (conceived according to the QM model) is irradiated with an EMG wave exhibiting sufficient wavelength, the generated conditions will facilitate reflection of the selected EMG wave from the applied electromagnetic wave spectrum. The wave selection depends on the actual periodicity of the material. The ideal frequency range of the transmitted wave is infinite bandwidth; theoretically, this condition can be satisfied by white noise. When the reflected part of the EMG wave is captured, it is advantageous to employ suitable evaluation tools, for example the Fourier transform, wavelet transform, or other techniques introduced above.

Benefits of Noise Spectroscopy

The contribution of noise spectroscopy consists in the use of an ultra-wideband signal to acquire, within a single instant of time, a response to the entire spectrum of electromagnetic waves. One of the possible ways of suppressing the negative sources of signals consists in the use of wideband signals such as white noise, and this approach can be further reinforced by analyzing the problem of absorption in the examined material. The indicated methods require a source of noise, a receiving and a transmitting antenna, and A/D conversion featuring a large bandwidth; for our purposes, the bandwidth of between 50MHz and 10GHz proved convenient. Until recently, however, it had not been possible to design an A/D converter of the required speed or to materialize devices with the above-mentioned bandwidth. Currently, high-end oscilloscopes are nevertheless available with a sampling frequency of hundreds of Gsa/s.

2. Noise source

At present, the appropriate type of source is supplied by certain manufacturers operating in the given field. Importantly, for the noise spectroscopy application, we require a comparatively large output power of up to 0dB/mW; the assumed bandwidth characteristics then range up to 10GHz. At this point, it is also necessary to mention the fundamental problem of finding active devices able to perform signal amplification at such high frequencies. Our requirements are thus limited by the current status of technology used in the production of commercially available devices; the highest-ranking solution for the bandwidth of up to 10GHz can be found only up to the maximum of 0dB/mW. In the noise spectroscopy experiments, we utilized a generator and an amplifier (NC1128A), Fig. 3. In order to verify the applicability of the noise spectroscopy laboratory arrangement (Figs. 5), we tested a metamaterial (periodic structure) designed for the frequency of 199.9 MHz (Fig. 4).

Fig. 3. The noise generator and power amplifier. The image shows the tested noise generator, whose output power is 0dBm in the frequency range of between 100kHz and 10GHz.

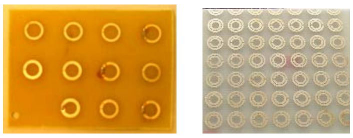


Fig. 4. The first tuned periodic structure tested to verify the noise spectroscopy measurement.

3. Antennas

Wideband antennas have long been used especially for the reception of specific signals. In certain cases, such traditional wideband devices also satisfy the requirements placed on UWB (ultra-wideband) systems. Traditional parameters utilized to describe technical characteristics of antennas may not be suitable for use in UWB systems [11]. The magnitude, impedance, bandwidth, and effectivity are interconnected in such a manner that their mutual proportion is indirect; these characteristics manifest themselves especially in electrically short antennas, the term denoting a layout where the largest dimension of the active part of an antenna is not larger than one tenth of the wavelength of the transmitted/received wave. An antenna electrically short in the entire frequency bandwidth cannot be simultaneously effective and exhibiting the impedance bandwidth (the range of frequencies at which the antenna is impedance matched) necessary for UWB applications. Within our research, some antenna types have been tested, including a Vivaldi antenna, a spiral two-leg antenna, and a hybrid fractal antenna combined with a spiral two-leg antenna (Fig. 5).

4. Method

The initial stage involved repeated transmission and sensing of both the signal provided by the noise generator and the external signals. The repetition was carried out for each sampled frequency, and the incident power spectrum was summed. Thus, we obtained the frequency dependence of the transmitted signal energy distribution. Generally, if the transmitter/receiver set is not located in a room with a defined spectral absorbance, we can expect uniform energy distribution within the whole frequency range. The record is, at its end, transformed to the frequency dependence of the specific power. In the described manner, we acquired the characteristics of the spectrum measurement background. At this point, the examined sample was placed in the support case (Fig.5, 6A, 6B); the sample for such application can be layered or periodic, and it is expected to provide the assumed frequency characteristic. Subsequently, repeated measurement was performed observing the above-outlined procedure. In the case of a markedly frequency-dependent background, the obtained characteristic can be corrected.

Fig. 7 shows the frequency dependencies of the measurement setup and the multi-layer material.

5. Conclusion

The research paper provides an elementary overview and description of the laboratory equipment for the noise spectroscopy measurement and the related experiments. Noise spectroscopy operations within the frequency band of between 10MHz and 10GHz can be performed using currently available technologies. The noise source comprised a generator (NC1108A) and an amplifier (NC1128A).

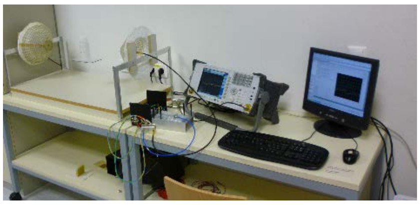
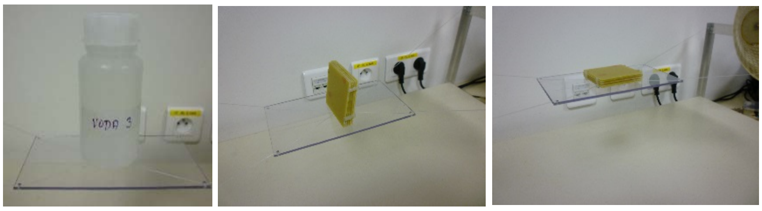


Fig. 5 The arrangement of the noise spectroscopy station (free room).



A B

Fig. 6 A liquid (nanomaterials) A, solid B sample arranged in the laboratory for the sensing and evaluation of the spectrum (no shielded chamber; free room).

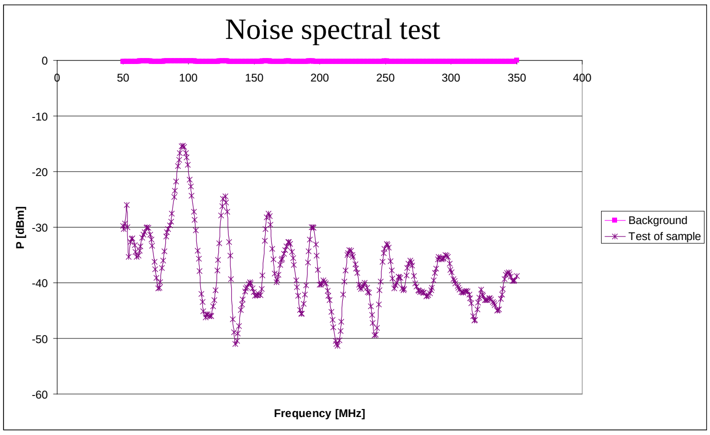


Fig. 7. The waveform and spectrum of the noise generator output for the measured sample; *f*=50-350MHz.

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