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Interdigital Sensors and Transducers

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Abstract- **This review paper focuses on interdigital electrodes—a geometric structure encountered in a wide variety of sensor and transducer designs. Physical and chemical principles behind the operation of these devices vary so much across different fields of science and technology that the common features present in all devices are often overlooked. This paper attempts to bring under one umbrella capacitive, inductive, dielectric, piezoacoustic, chemical, biological, and microelectromechanical interdigital sensors and transducers. The paper also provides historical perspective, discusses fabrication techniques, modeling of sensor parameters, application examples, and directions of future research.**

Index Terms— **Dielectric measurements, interdigital sensors, non- destructive testing (NDT), sensor design, sensor modeling, spec- troscopy, surface acoustic waves (SAWs), transducers.**

I. INTRODUCTION

A. Motivation for This Paper

Interdigital electrodes are among the most commonly used periodic electrode structures. Recent advances in such fields as nondestructive testing (NDT), microelectromechanical systems (MEMS), telecommunications, chemical sensing, piezoacoustics, and biotechnology involve interdigital electrodes in very different ways. At the same time, a number of common features are shared among these applications. The purpose of this paper is to outline common features and to highlight the differences of sensor geometry, manufacturing techniques, choice of materials, analytical and numerical modeling, design optimization, system integration, and data analysis. It is difficult and perhaps even excessive to maintain equally deep and comprehensive treatment of all these subjects. Instead, the fringing electric field sensors are given the deepest emphasis in this manuscript. Significant aspects of other types of sensors are discussed, while repetition is avoided. References are provided to major review papers and books in each section devoted to a particular field of interdigital electrode applications, such as dielectric imaging, acoustic sensors, and MEMS.

It is not possible to develop a universal sensor and a universal parameter estimation algorithm that would provide the maximum information about material properties in all applications. Each application requires a judicious choice of sensor design and associated parameter estimation algorithms. As a technical system develops, the requirements for each element become clearer and affect the requirements for each element of the trinity shown in Fig. 1. For example, it may become clear during the development stage that the one- sided access to the material under test (MUT) is not necessary due to the specifics of the manufacturing process. In this case, the electrode layout design should not be limited to interdigital structures only. The dual-sided access has advantages of larger, easily measurable capacitances and a more uniform field distribution. The examples of appropriate matching of sensors and parameter estimation algorithms with different applications are encountered throughout this paper.

piezoacoustic transducers, is that only a single-side access to the test material is required. One can penetrate the sample with electric, magnetic, or acoustic fields from one side of the sample, leaving the other side open to the environment which can allow absorption of gas, moisture, or chemicals, which can change electrical properties of the MUT. A sensitive layer of chemical or biological nature deposited over the electrodes can also interact with a gas or liquid environment, allowing monitoring of concentration of chemicals in such materials as air, transformer oil, or the human body. In some situations, the other side of the material sample may be too far away or inaccessible due to design limitations for an electrode so that one-sided access is essential.

Control of signal strength. By changing the area of the sensor, the number of fingers, and the spacing between them, one can control the strength of the output signal. A tradeoff between the signal-to-noise ratio and the minimum sensing area is selected based on the application requirements. In microchip sensors, the size of the sensitive area is usually of little consequence, whereas in imaging devices it plays a major role.

Imaging capability. A relatively new field of research is interdigital frequency-wavelength dielectrometry, a close relative of electrical impedance tomography. This technology employs interdigital electrode pairs of variable spatial periodicity. The depth of penetration of quasi-static electric field lines into the material is frequency independent and proportional to the spatial wavelength, defined as the distance between the centerlines of neighboring electrodes of the same polarity. The differing penetration depths of multiple wavelengths make possible spatial profiling of dielectric and conduction properties and geometry of semi-insulating materials. That is, properties of individual layers across the thickness of a stratified medium can be determined without direct access to each layer. Movement of the sensor along the material surface with subsequent signal processing makes possible, in principle, three-dimensional (3-D) imaging of dielectric properties of insulating materials. The dielectric properties can be related to many other phys- ical properties, such as porosity, density, structural integrity, and chemical content of materials under test. At very high radian frequency, the skin depth further limits the penetration of electric and magnetic fields into a medium with conductivity and magnetic permeability Multiple physical effects in the same structure. In addition to sensing applications, fringing electric fields are used increasingly to generate mechanical forces, especially in MEMS. Scaling of motors and actuators to the distances on the order of tens of micrometers make electric fields a feasible choice for actuation of moving parts, whereas mag- netic fields dominate the traditional macro scale designs. A strong electric field enhancement at the ends of interdigital electrodes generates a lateral force, which is used for comb displacement. Electrical force levitation is achievable using fringing fields in the direction perpendicular to the interdigital pattern plane.

Simplified modeling. When the aspect ratio of the electrode finger length to the spatial wavelength is large, the numerical simulation and theoretical modeling is greatly simplified because it can be done in the approximate two-dimensional (2-D) limit rather than in 3-D. For this reason, interdigital electrodes are popular when extensive modeling is required for the interpretation of experimental results. For example, elaborate models of electrical or acoustical interactions of interdigital sensors and trans- ducers with stratified media are often developed using 2-D approximations. There is a trend, however, toward full 3-D simulations, taking advantage of continuing dramatic increases in computer speed.shows the frequency spectrum for acoustic and electromagnetic phenomena and instrumenta- tion ranges. The lowest frequencies, starting at 1 Hz are used for laboratory measurement of conduction properties, where low-level conduction phenomena are difficult to otherwise measure. The frequencies below 1 Hz are not suitable for real-time industrial monitoring and are used mostly in the laboratory studies of physical phenomena. The characteristics of wave propagation drive the selection of frequency ranges above 1 Hz. Especially significant are such properties as spatial resolution, penetration depth, attenuation, and external interference. Another important property of the SAW is its extremely low velocity, about 10 times that of electromagnetic waves [41]. This property makes an acoustic wave structure ideal for long delay lines. Because of this low velocity, acoustic waves have very small wavelengths, which offer dramatic reductions in the size of SAW devices. Also, SAWs have low loss during propagation.

II. SAW DEVICES

IDTs are the building blocks of surface wave filters. Normally, two IDTs are used to build a SAW sensor. One IDT is photodeposited on the highly polished surface of a precisely oriented piezoelectric crystal. When a voltage is applied to the contact pads, an electric field distri- bution is established between spatially periodic electrodes. Because of the piezoelectric effect, an elastic strain distribu- tion with periodicity is generated. The transducer operates with the highest efficiency when the excitation frequency is such that the physical distance between alternate lines corresponds to the wavelength of the surface wave. The SAW propagates in two opposite directions because of the sym- metric structure of IDTs. A second IDT is deposited on the other end of the substrate to detect the SAWs. Detection oc- curs through inverse piezoelectric coupling. RF signals are generated at the output of the second IDT. Acoustic termina- tions are designed at each end of the substrate to absorb the bidirectionally launched surface wave.

The frequency, bandwidth, and time response of the IDT are variables that can be controlled by the number of finger electrode pairs in both transducers, the distance between the generating and receiving transducers, the overlap region of the fingers, and the width and spacing of adjacent fingers [43]. The frequency range of operation of SAW transducers is between 50 MHz and several GHz [44]. The velocity of these waves depends on the dielectric and mechanical properties of the

MUT. The phase shift of the transducer signal is

(5)where is the wave speed, is the

frequency of excitation, and is the length of the transducer. Normally, the electroacoustic wave propagation characteristics are only weakly influenced by the dielectric properties of the sensitive layer or MUT [45].

The most common IDT is a uniform IDT, whose finger length and overlap of finger projections onto a line parallel to the each finger do not vary. When a SAW sensor is used for bandpass filters and pulse compression filters,the structure is nonuniform—the finger projection overlap varies. This structure change is called apodization. When an impulse voltage is applied to the apodized transducer, a group of generated SAWs propagate along the substrate, following the outline of the finger projection overlap. At the receiving transducer, each waveform generates a voltage corresponding to the overlap. An apodized transducer increases the versatility of the SAW device, since it allows the synthesis of a diversity of sophisticated filters. Also, the customization of electrode configuration can provide a desired transfer function for a SAW device.

The usage of apodized transducers causes the problem of decreasing surface wave velocity with propagation through metal electrodes. Let us consider the electrodes indicated by solid bars in the long transducer in Fig. 8. The surface wave propagating along the middle of this transducer crosses more electrodes, so it is slowed much more than a wave propagating closer to the contact pads. Severe distortion of the wave profile takes place after it propagates through the apodized transducer. "Dummy" electrodes are sometimes utilized for the remedy of this problem, which is shown in Fig. 8 by the dashed bars. This kind of electrode does not affect the electrical properties of the transducer, but makes the SAW velocity remain uniform when propagating through transducer electrodes.

III. SENSOR FABRICATION

A. Substrates

1) Physical Properties:

Flexible versus rigid. The choice of substrate thickness and the degree of substrate flexibility depends on the application. Flexible substrates with thin electrodes are advantageous when the sensor head is expected to conform to the surface of the MUT. Representative applications of such a design include measurements performed at an airfoil surface, turbine blades, aircraft rotor blades [46], and curved transformer pressboard insulation [47].

On the other hand, rigid substrates or rigid electrode designs are advantageous in noncontact measurements. In this

case, it is important to maintain a well-defined geometry of the electrode structure in order to be able to take advantage of model-based parameter estimation algorithms.

Hydrophilic versus hydrophobic. Direct measurement of moisture or other material properties in the bulk of material typically suggests use of hydrophobic substrates, especially for imaging applications. Absorption of moisture by the substrate is undesirable because it adds another disturbance factor to measurements. On the other hand, measurements of moisture in liquid materials are often accomplished through the use of a hydrophilic substrate and by correlating the change of substrate properties with the change of material properties. This method adds delay to measurements because the substrate and the MUT must be in equilibrium to achieve correct readings.

2) Centimeter and Millimeter Scale Substrates:

Kapton. Polyimide is a frequent choice of the sensor substrate, especially for flexible sensor heads. Polyimides are omnipresent in the modern printed circuit board industry. The manufacturing techniques for them are well developed, and their properties have been investigated under many different conditions and reported in a large number of publications. Examples of designs and use of sensors manufactured with polyimide substrates are reported in [19], [25], and [48]–[51].

Polyimide sensors can operate in temperatures up

to 350 C, which makes them an attractive choice for a power transformer environment where

operating temperatures reach 100 C [52]. Polyimide is a slightly hydrophilic material, being able to absorb moisture up to 3% of its dry weight [24], [50]. Because of the high dielectric permittivity of water in comparison with the dielectric permittivity of dry polyimide, even relatively small amounts of water increase the dielectric permittivity of polyimide by as much as 30% [53], [54]. Table 1 shows the variation of the electrical properties of Kapton with relative humidity at room temperature, assuming that the material has been allowed enough time to achieve moisture concentration equilibrium with the ambient environment. For calculations involving absolute water content at room

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