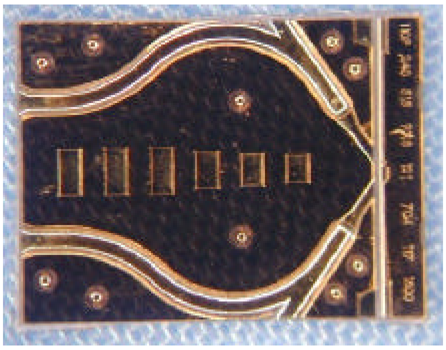
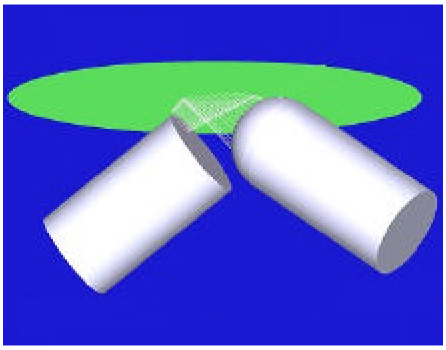
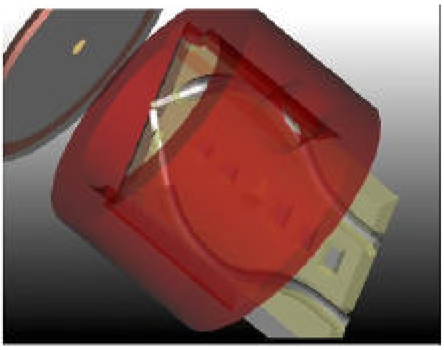
The Optical Microphone

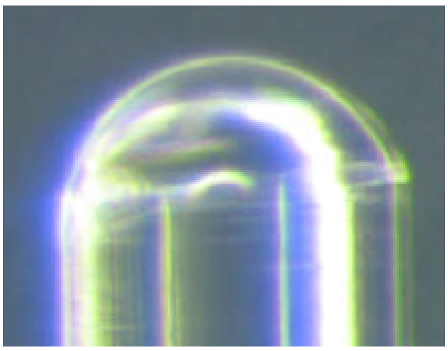


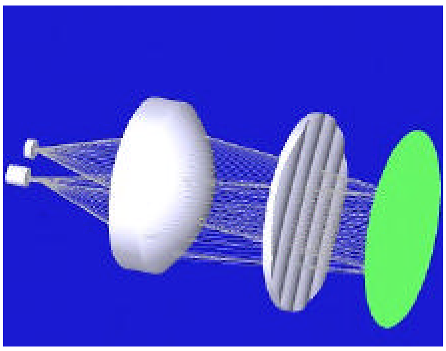
Introduction of a new technology

written by Otto Kroymann









The Optical Microphone

Introduction of a new technology

A research paper submitted in partial fulfilment of the requirements
of the Degree of

BA(Hons) Sound Technology

At

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By

Otto Kroymann

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ABSTRACT

For over half a century there seemed to be little development in microphone technology. Condenser microphones have proved to be very reliable and have very well established on the market. In live sound engineering the dynamic microphone is still the leader. It seemed to be not much use or sense in a new, a different technology. However, times change persistently and environmental conditions as the steadily growing problems in live sound with electromagnetic interference by all kind of telecommunications or just the requirements on size of a microphone make a new technology inevitable. The optical microphone offers a viable solution to these demands. Introducing this brand new technology, which has not yet started its way on the market, this research paper aims to present its advantages and possibilities.

ACKNOWLEDGEMENTS

Thanks to the development teams of Sennheiser electronics GmbH & Co KG in Hanover, Germany, and the Fraunhofer Institute for Applied Optics and Precision Engineering in Jena, Germany, for their time and support.

Special thanks to Prof. Dr. Jürgen Peissig and Dr.-Ing. Wolfgang Niehoff, who took the time to show me around in the development department of Sennheiser electronics and gave me a deep insight into the development of the optical microphone.

Thanks as well to Dr. Peter Schreiber from the Frauenhofer Institut for his time during my visit there and numerous e-mails.

CONTENT

1. INTRODUCTION

The quality of a microphone and its flexibility in usage is important in nearly all performances containing music in any form or even speech in our time. Times when artists performed live without any technical support are longest gone and in today's world the technology has become a creative part of the performance. The focus is no longer only on sound reinforcement but also on the creative use of the microphone in order to enrich the impression of the show.

Thriving on the wish to enrich the impression microphones differ in numerous designs by multiple manufactures and even particular products specifically built for their usage such as dedicated vocal or single instruments microphones.

Even though there are these huge differences between microphones, and sound engineers and artists make it a science to select the right microphone for the right application, microphones can still today only be categorised into two basic operating principles.

> "For almost sixty years, the process has been one of refining designs, lowering the cost of production, and exploring new market outlets for the wealth of basic research done (...)"[1]

These two basic operating principles, the dynamic and the condenser microphone, have ruled the market over decades and still continue to do so. Only now microphone technology seems to get a new, unfamiliar impulse by new developments on the market.

Besides this stimulus leading to further development of the traditional techniques as the silicon microphone, a complete new technique is due to change the market: the optical microphone. Not yet fully grown, but only a tick away from going into mass-production, this new technology may be the future of microphones.

Introducing the optical microphone, this research paper seeks to give an idea of its function and analysis its possibilities and advantages as well as its problems.

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[1] D. Davis, C. Davis: *Sound System Engineering, 2nd Ed, p. 5.*

Starting with an analysis of the actual situation in microphone technology, the research paper gives in chapter two an outline of the positions of the two predominant operating principles on the market. Considering the stronghold that these two basic physical principles of microphone technology, dynamic and condenser, have build on this market, it is imperative for this research paper, examining and analysing a new emerging technology, to ensure a thorough understanding of these competing physical principles. Besides this review of the current technical situation the chapter will analyse the steadily growing problem in the application of these microphone technologies. By the means of a statistic graph it is demonstrated how environmental conditions change and therefore require a new approach towards interference in sound technology.

This leads directly to the new technology of the optical microphone introduced in chapter three. Even though not fully accomplished the history of development of the optical microphone is already quiet old. To develop a broader understanding of the considerations leading to this new technology and the way it was established the chapter has a look insight its historic root. After describing the basic principle, the chapter introduces two different designs of the optical microphone developed by *Sennheiser electronics GmbH & Co. KG* in Hanover, Germany, and the *Fraunhofer Institute for Applied Optics and Precision Engineering* in Jena, Germany.

Subsequent this technical review, chapter four looks at the optical microphone in the application of live sound reinforcement. It will thereby not only concentrate on the technical advantages of the design but also highlight the new creative possibilities inspired by this technology. It will thereby not only concentrate on the technical advantages of the design but also highlight the new creative possibilities inspired by this technology. Since the optical microphone is not a flawless miracle, the chapter will analyse also the problems facing the new technology. Due to the fact that the optical microphone only just emerges and the only specimens existing are laboratory demonstrators, the chapter ‘the optical microphone in application’ is only a theoretical approach based on the microphone’s possibilities and the results of the initial testing. Since the optical microphone is a complete novelty that is not fully on the market yet, this research paper was developed in close co-operation and with the help of the developing teams of *Sennheiser electronics GmbH & Co. KG* in Hanover, Germany, and the *Fraunhofer Institute for Applied Optics and Precision Engineering* in Jena, Germany.

Limited in space and time and due to the fact that looking at the whole field of the application of the optical microphone would lead into much longer exegesis, this research paper focuses on the direct field of sound technology. The research paper especially concentrates on live sound reinforcement as the optical microphone unfolds most of its advantages in this field.

2. SITUATION ANALYSIS

Since the early days of cinema and the beginning of sound reinforcement, the motion pictures gathered followers and the performing arts industry embraced the evolving technology. Driven from the wish to leave an imprint of performances and great concerts, the development of audio recording

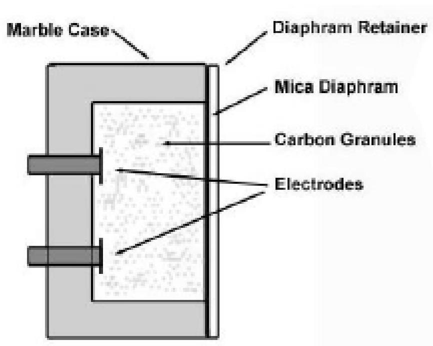

Figure 1 Schematic of the carbon microphone

imperatively needed the development of microphone technology[2]. In succession technology became an integrative and essential part of the performing arts industry. The making of stars and the making of money became closely inter-linked with the capability of refining the art of recording and the art of developing and, finally, using a microphone. At the same time the microphone started to play also in the adjacent field of live performances a more and more central role. As theatres grew and audiences enlarged the possibilities of reaching every single member of the audience by sheer natural means became smaller and smaller[3].

But also besides the glamorous stages of the performing arts industry a desperate need for the improvement of microphone technology arose from the struggle for political and economical power. Growing masses and growing political interest and education needed means of distribution and reinforcement in gatherings and radio broadcast[4].

The carbon microphone was the only available microphone and even though it served well, the audio quality was, especially concerning the sensitive field of recording, far from sufficient[5]. Despite being the first available microphone, the carbon microphone did not play a significant role for the later microphone technology due to its inferior sonic quality.

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[2] J. Webb: *Twelve Microphones that changed History* on http://www.blueson.se/twelvemicrophones.htm, 11.04.2005.
[3] W. Ahnert, F. Steffen: *Beschallungstechnik, Grundlagen und Praxis,* p. 5.

[4] J. Schmidt: *"Die Politik zum Erlebnis machen... "Politische Bildung für Erwachsene zwischen Schiff und Theaterbühne* on: http://www.rahvaylikool.ee/socrates/4.htm, 11.04.2005.
[5] S. E. Schoenherr: *Microphones part I: The carbon era* on http://history.acusd.edu/gen/recording/microphones1.html, 11.04.2005.

A leap in technology brought the invention of the condenser microphone by Georg Neumann in 1928[6], or according to other sources by E.C. Wente in 1917[7], and a few years later the invention of the dynamic microphone[8]. These two technologies have been developed further since then. Both microphone technologies will be further illuminated later in this research paper.

Having evolved to a high standard and a very high level of diversification[9] these principles are still in use today. In fact, after nearly sixty years these two designs are the only two basic principles applied in the modern microphone technology[10]. As today's microphones have become a reliable technology, the dynamic microphone can surely be seen as the market leading principle, regarding especially the market of live sound reinforcement[11]. Nevertheless, also the condenser microphone, due to the sensitivity of the design pruned to be a purely 'indoor' studio microphone, has today made its way onto live stages and is well established in the field of live sound reinforcement[12]. It is even in

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[6] Wikipedia: *Kondensatormikrofon* on http://de.wikipedia.org/wiki/Kondensatormikrofon, 11.04.2005.
[7] E. Erb: *Mikrofonsysteme* on http://www.radiomuseum.org/dsp_forum_post.cfm?thread_id=47242, 11.04.2005.
[8] J. Wuttke: *Mikrofonaufsätze* on http://www.schoeps.de/D-2004/PDFs/Mikrofonbuch_komplett.pdf, 11.04.2005.
J. Webb: *Twelve Microphones that changed History* on http://www.blueson.se/twelvemicrophones.htm, 11.04.2005.
[9] T. Görne: *Mikrofone in Theorie und Praxis*, 2nd Ed., p. 27.
J. Eargle, C. Foreman: *Audio Engineering for Sound Reinforcement*, p. 55.
[10] J. Eargle: *The Microphone Book*, p. 108-124.
[11] W. Ahnert, F. Steffen: *Beschallungstechnik – Grundlagen und Praxis*, p. 131.
[12] G. Ballou: *Dynamic Mikrophones* in G. Ballou(ed): *Handbook for Sound Engineers, The new Audio Cyclopaedia*, 2nd Ed., p. 400.

some places on the verge of taking over the leadership on the live sound reinforcement market.

These two basic principles of the dynamic and the condenser microphone have dominated the microphone market and are so important for the microphone technology that it is vital for the introduction of a new technology to fully understand them, first.

2.1. THE DYNAMIC MICROPHONE

The dynamic or, to be more exact, moving coil microphone is the simpler of the two principles. The basic functionality is analogue to the operating principle of a "loudspeaker in reverse"[13]. As shown in figure 2, the transducer assembly of the dynamic microphone consists of three main

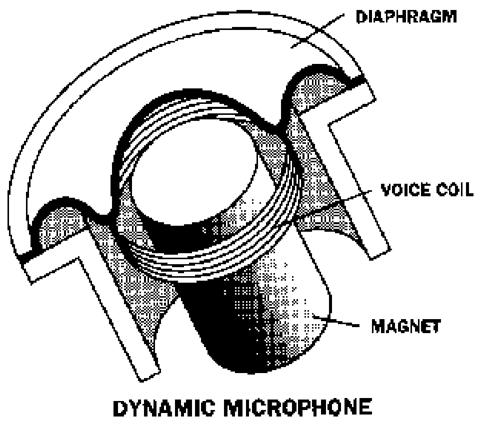

Figure 2 Schematic design of the dynamic microphone

[13] Info.aus-germanien.de: *Dynamisches Mikrofon* on http://infos.aus-germanien.de/Dynamisches_Mikrofon, 11.04.2005.

parts: The diaphragm, a magnet, and the coil. The operating principle is based on the physical principle of electric induction[14]. The body part of the design is the permanent magnet, today usually not a normal ferrite or cobalt magnet but rather a neodymium or an alnico magnet, in which the coil is moving freely an air gap inside the magnet. This coil is permanently and rigidly attached to the actual diaphragm of the microphone. Therefore, the impinging sound wave excites the diaphragm and with it also the voice coil. By moving within the magnetic field electricity is induced in the voice coil[15]. This voltage represents in its amplitude and its polarity the movement of the diaphragm and gives an electrical equivalent of the impinging sound wave. The major downside of this operating principle is the fact that the combined masses of the diaphragm and the voice coil represent a not negligible inert mass which the impinging sound wave has to excite and set into motion[16]. Therefore, the frequency response, especially in the high frequency band, tends to suffer as does the impulse response. This derives directly from the inherent inertia of the assembly[17]. The answer today to this problem is in fact the second microphone technology, the condenser microphone.

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[14] Eventtechniker: *Dynamisches Mikrofon* on http://www.eventtechniker.de/body_ton.htm#Dyn-Mikrofon, 11.04.2005.
[15] J. Eargle, C. Foreman: *Audio Engineering for Sound Reinforcement*, p. 55.
[16] J. Eargle: *The Microphone Book*, p. 108-124.
[17] W. Ahnert, F. Steffen: *Beschallungstechnik – Grundlagen und Praxis*, p. 132.

2.2. The Condenser Microphone

Following a completely different physical principle, which is distantly related to the carbon microphone, the condenser microphone is able to overcome some of the problems of the dynamic microphone.

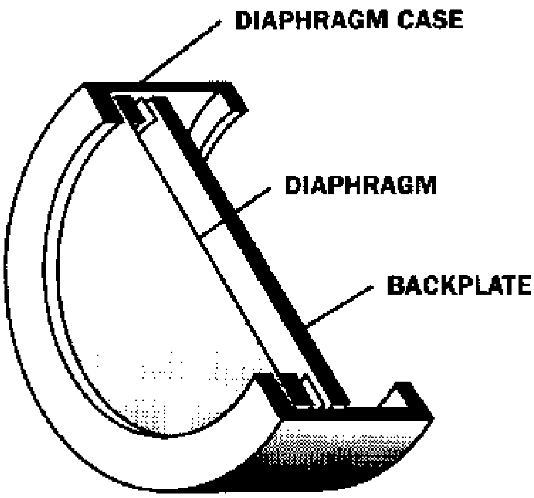

Figure 3 Assembly schematic of a condenser microphone

The basic operating principle of the condenser microphone is, as suggested by the name, that of a condenser[18]. Two electro-conductive plates facing each other are polarised by an electrical charge and are therefore generating an electrical field[19]. If one of these plates is now moved towards or away from the other the electrical charge and with it the electrical field is changing[20]. In the application of the condenser microphone, as shown in fig. 3, these two condenser plates

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[18] J. Eargle, C. Foreman: *Audio Engineering for Sound Reinforcement*, p. 57.
[19] Eventtechniker: *Kondensator Mikrofon* on http://www.eventtechniker.de/body_ton.htm# Kondensator-Mikrofon, 11.04.2005.
[20] Wikipedia: *Kondensatormikrofon* on http://de.wikipedia.org/wiki/Kondensatormikrofon, 11.04.2005.

form the core parts of the design. One plate becomes the 'back plate', a rigidly mounted plate which is integral part of the microphone casing. The opposite plate is a flexibly mounted electro-conductive foil, which is in this microphone design acting as the microphone diaphragm. This diaphragm, in contrast to the dynamic microphone, has no additional parts attached to itself and is therefore pruned to subtend much less mass to the arriving sound wave[21]. Hence the arriving sound wave has to overcome much less inertia. Even though this design has solved this particular problem, it still is far from being perfect. Over a long period, condenser microphones were deemed not to be robust enough to withstand the physical stress in the field of live sound reinforcement. This is, due to improved materials and manufacturing processes, about to change.

Regardless of all technological improvement, unfortunately it remains the fact that both the dynamic and the condenser design suffer from the same symptom: The unchallengeable fact that they both rely on electromagnetic basic principles. Therefore, both transducer designs are susceptible for both electromagnetic interference (EMI) and radio frequency interference (RFI)[22].

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[21] W. Ahnert, F. Steffen: *Beschallungstechnik – Grundlagen und Praxis*, p. 130.
[22] T. Görne: *Mikrofone in Theorie und Praxis*, 2nd Ed., p. 53.

2.3. GROWING PROBLEMS OF 'TRADITIONAL' DESIGNS

As electromagnetic fields are generally low in intensity and the range is definitely not incredibly wide[23], it may seem that the susceptibility for EMI and RFI is not a real threat to the end-user of these transducer designs in the application of live sound reinforcement. This fact, being true for electromagnetic interference, is to be challenged, especially concerning the radiating range, if it comes to radio frequency interference[24]. But again the field strengths, compared to other sources of noise and unwanted interference in the field of live sound reinforcement, seems at first to be negligible[25]. However, considering today's world, this view is most likely to be fundamentally changed.

Over the last few years the world has dramatically changed. The need for every individual to gain access to more information and telecommunication has reached every corner of our daily lives. The pace of living has incredulously accelerated and people feel more than ever the need 'to be connected'. This fact becomes most obvious and very easy to grasp looking at the statistics of mobile telephone networks and the figures of subscriptions. As

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[23] W. König: *Aufgaben des BfS im Bereich des vorsorgenden* Verbraucherschutes in BfS Bundesamt für Strahlenschutz: *Jahresbericht 2002*, p. 7.
[24] Bayerisches Landesamt für Umweltschutz: *Schirmung elektromagnetischer Wellen im persönlichen Umfeld*, p.9.
[25] G. Brix: *Erfassung und Bewertung der Strahlenexposition von Patentinnen und Patienten durch moderne Bildgebungsverfahren* in: Bundesamt für Strahlenschutz: *Jahresbericht 2003*, p. 10.

shown in fig. 4, the figures concerning the spreading of the use of mobile telephones are growing at a very high rate. While the network penetration is reaching the full coverage, the number of subscribers is still growing at over ten percent per year. Unfortunately, especially the figures of the network penetration might lure into false hope as it seems that the problem can not become worse once the full coverage is reached. This is quite deceptive as, in succession of the quality improvement and the addition of new services, such as Bluetooth or 'push-to-talk', the networks undergo a steady improvement and strengthening of the coverage. Especially the newest addition to the mobile network services, 'push-to-talk' is hereby growing at an alarming rate[26].

> "According to an analysis of the American market research company *In-Stat* the figure of US American users of the 'push- to-talk' (PtT) service, or respectively the 'push-to-talk over cellular' (PoC), will increase from 16,8 bn today to 33,6 bn in 2009."[27]

But not only the communication sector is undergoing a very fast and extensive growth process, also the sector of information services such as radio network or television stations, grows at a never before seen rate[28].

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[26] E. Batista: *'Push-to-Talk' spreading fast* on http://www.wired.com/news/business/0,1367,60554,00.html, 13.04.2005.
[27] Inside-handy.de: *Push-to-Talk wächst weltweit stetig* on http://www.inside-handy.de/news/2994.html, 13.04.2005.
[28] Regulierungsbehörde für Telekommunikation und Post: *Jahresbericht 2004*, p. 42.

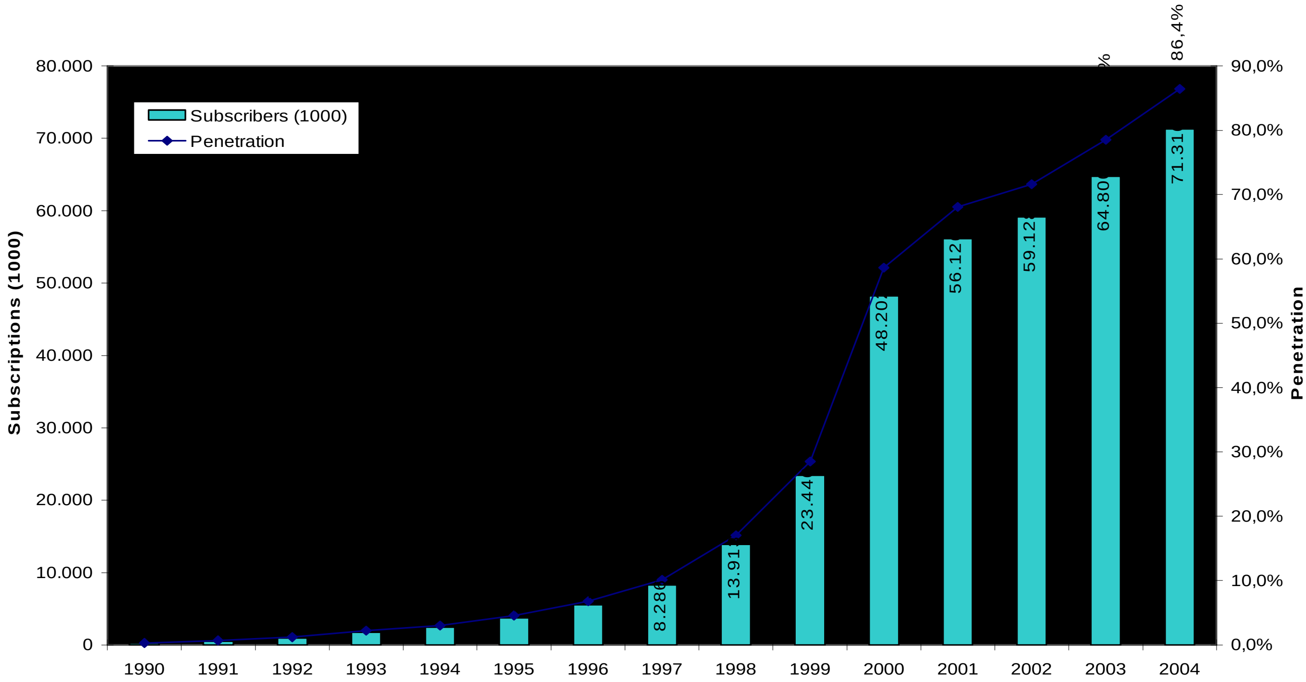

Figure 4 Subscription and Network Penetration of mobile phones in Germany

Being as it is, the fact that electromagnetic pollution of the environment and in the occasion of live concerts or large scale live performances grows at an alarming rate is an undeniable fact. Considering the situation of large scale concerts, organisers and with them also the sound engineers face an audience where each member has its own mobile telephone. In addition to these possible 30000 telephones in the audience, the fact that also performers and even the crew members rely more and more on radio technology as means of communication is even further contributing to the problem of electromagnetic interference. The overall amount of radio frequency and electromagnetic interference existing in the vicinity of stages, places of the use of live sound reinforcement, or the transmission via radio or television reaches a critically high level. Therefore, situations as shown, and even more heard, in the video clip attached in the appendix (Appendix B) are doomed to happen more often. The video visualises quite impressively the effect of electromagnetic interference generated by a mobile telephone in the situation of a live broadcast of an interview. After contacting the television station's sound engineer, it was confirmed that this noise was generated by the mobile telephone in question and picked up via the microphone sitting right on top of the telephone.

Returning to the fact that telecommunication, information, and multimedia distribution are more and more a central and integral part of our society and are therefore accompanied by an incredible multiplication of appliances, the intensity and the power of the electromagnetic field engulfing the society are bound to grow at a proportional rate. Therefore, possible electromagnetic interference and also radio frequency interference is a problem in being, which directly affects the field of live sound reinforcement and everyone working within it.

3. Optical microphone

The answer to these problems can be seen in the optical microphone. This new technology leaves the electromagnetic principles of the traditional microphone technologies behind. Discussing this revolutionary new technology it is absolutely essential to understand the basic underlining principles of its operation. The optical microphone in its simplified version can be seen as an optical distance sensor[29] registering the actual distance of the diaphragm to the reference of the optical fibres at

[29] W. Lukosz, P. Pliska: *Integrated Optical Interferometer as a Light Modulator and Microphone* in: Sensors and Actuators A 25-27, p. 337-340.
A. Sander: *Optisches Mikrofon* Offenlegungsschrift DE 2853336 des Deutschen Patentamtes.

any given point in time and therefore analysing the speed and amplitude of its movement which is in it an exact replica of the arriving sound wave[30].

3.1. The History

Even though the optical microphone is a completely new technology, the roots of its development are on the contrary nearly as old as microphone technology itself.

The first notions of an optical transducer technology derive of Alexander Graham Bell in 1880[31]. When working on the development of the telephone Alexander Bell planned at first to implement an optical transducer in his design as he thought light would be a more suitable and faster way of transmitting the signal[32]. His transducer designs amazingly resembled the

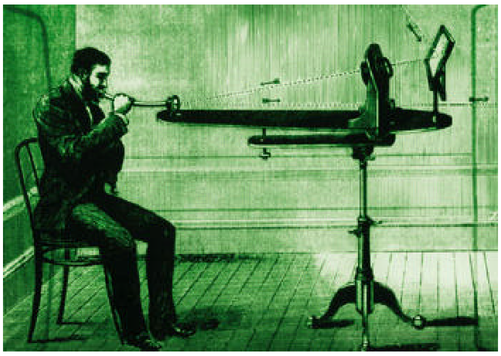

Figure 5 Photophone transmitter by A.G. Bell, 1880

[30] D. Garthe: *Faser- und Integriertoptische Mikrofone auf der Basis Intensitätsmodulierender Membran-Abtastung*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 214, p. 2.

[31] P. Schreiber et al.: *Fibre-coupled optical Microphones*, AES116th Convention, Berlin 2004.

[32] Inventors: *Alexander Graham Bell's Photophone* on http://inventors.about.com/library/inventors/bltelephone3.htm, 11.04.2005.

designs developed today[33]. The major difference was that he did not utilise optical fibres, as those had not been invented yet, but thought of relaying the beam of light through air. His, in those days nearly unsolvable, main challenge was in fact the re-conversion of the modulated light beam into acoustic energy[34]. Having hit this dead-end he abandoned this idea and it became forgotten.

In the 1920's the German physicist Walter Brinkmann, after having discovered the photoelectric properties of selenium, pursued the idea again, in co-operation with several artists of the Bauhaus movement, such as Lásló Moholy-Nagy. They developed an instrument called the optophon[35]. Its idea was to convert light into sound. In difference to the optical microphone the light source was not modulated by sound but was generated in the desired fashion[36]. The further development was abandoned again, this time due to the upcoming Second World War. After the war the

Figure 6 Photophone receiver by A.G. Bell, 1880

[33] I. Fromm: *Optophon – ein optisches Übertragungssystem für Sprache* in: Frequenz 32, Nr. 12, p.357.
[34] A. G. Bell: *On the Production and Reproduction of Sound by Light* in: American Journal of Science 20 (1880), p. 311.
[35] H. de la Motte-Haber: *Klangkunst, Ausstellungskatalog Sonambiente,* Festival für Sehen und Hören, Akademie der Künste Berlin, p. 69.
[36] V. Straebel: *Eine kleine Geschichte der Photozelle in Musik und Klangkunst* on http://www.straebel.de/praxis/text/t-photozellen.htm, 11.04.2005.

development was not being picked up again as the main focus lay on the 'traditional' microphone technology.

The idea of an optical microphone, even though theoretically every now and then appearing, rested until an Israeli company, *phone-or*, resumed the idea. In co-operation with well known company *Sennheiser* the research on the optical microphone was started in the early 1990's. After the first successful testing of a new design the clear mismatch of the intended direction of the two research partners became apparent. This resulted in the break-up of the research and development co-operation between *Sennheiser* and *phone-or*. Unfortunately, due to legal reasons, *Sennheiser*, not in possession of the relevant patents, had to re-establish the whole research. This time, in order to acquire their know-how in optics, they struck a co-operation with the *Fraunhofer Institute for Applied Optics and Precision Engineering* in Jena, Germany. Thriving on this co-operation the two partners developed two individual designs relying on the same basic principle. The design of *Sennheiser* approached the challenge from the acoustic point of view whereas the design of the *Fraunhofer Institute* came clearly from a more optical point of view.

3.2. THE PRINCIPLE

The underlining physical principle of the diaphragm motion detection can be achieved in three different ways[37]. These are all related to the modulation of the light emitted from the used light source. The emitted light can either be modulated in amplitude (or intensity)[38], phase (or frequency)[39], or in polarity[40]. To utilise the two latter principles, the original beam emitted of the light source has to be split up before the modulation[41] by the microphone diaphragm in order to obtain a reference signal which the modulated signal could then be compared to[42]. In the later stages of these principles the signal would have to be converted into an intensity modulated beam of light[43], after the comparison stage. This is due to the fact that the usual photo detectors are only able to recognise and to

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37 J. A. Bucaro, N. Lagakos, J.H. Cole, T. G. Giallorenzi: *Fiber Optic Acoustic Transduction* in: W. P. Mason, R. N. Thurston (ed.): *Physical Acoustics*.

38 T. G. Giallorenzi, J. A. Bucaro, A. Dandridge, G. H. Sigel, J. H. Cole, S .C. Rasleigh, R. G. Priest: *Optical Fiber Sensor Technology*, IEEE J. Quant. Electr. QE-18 Nr. 4.

39 R. Herber: *Faseroptische Sensoren für Luftschallanwendungen*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 125.

40 D. Garthe: *Faser- und integriertoptische Mikrofone auf der Basis intensitätsmodulierender Membran-abtastung*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 214, p. 8-9.

41 K. Fujimura, M. Matsumoto, K. Hattori, H. Naoni: *Fiber-optic-acoustic sensor using a Fabry-Perot interferometer*, 2nd joint meeting of ASA and ASJ, Paper GG 11.

42 R. Herber: *Faseroptische Sensoren für Luftschallanwendungen*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 125.

43 J. A. Bucaro, N. Lagakos, J.H. Cole, T. G. Giallorenzi: *Fiber Optic Acoustic Transduction* in: W. P. Mason, R. N. Thurston (ed.): *Physical Acoustics*.

convert amplitude modulation into changing voltages[44]. Therefore, it is preferable, in order to keep the construction of the microphone as simple as possible, to implement the principle of amplitude or intensity modulation in the optical microphone[45]. This is even more so as the other principles would require far more expensive parts. Additionally, tests under laboratory conditions showed that the advantage of their implementation would be negligible[46].

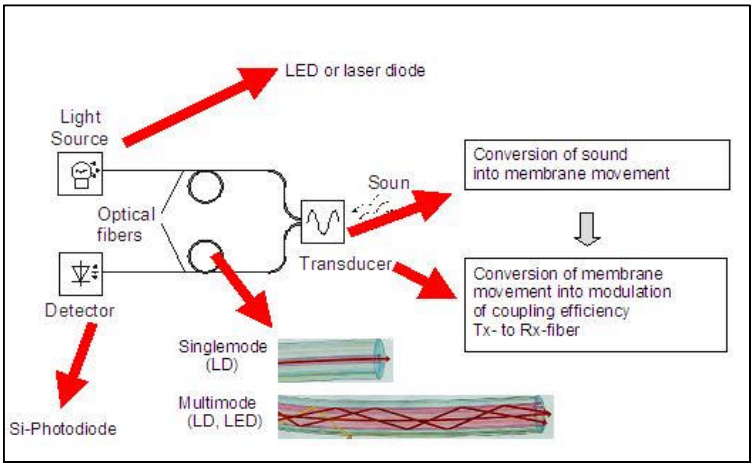

Figure 7 Schematic of the optical transducer

The optical microphone consists in its basic assembly of a very simple set-up (fig. 7). The light source, which is in a normal application either a light emitting diode (LED) or a laser diode (LD), sends the light through an optical fibre towards the diaphragm. On exiting the sending optical fibre the

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[44] D. Garthe: *Faser- und integriertoptische Mikrofone auf der Basis intensitätsmodulierender Membran-abtastung*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 214, p. 8-9.
[45] T. Fricke-Begemann, J. Ihlemann, R. Weichenhain: *Mikrooptiken zur Verbesserung eines optischen Abstandsensors und Mikrofons*, DGaO-Proceedings 2004.
[46] D. Garthe: *Faser- und integriertoptische Mikrofone auf der Basis intensitätsmodulierender Membran-abtastung*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 214, p. 38.

beam of light is subsequently reflected by the diaphragm which is equipped for this purpose with a vacuum deposited gold plate.
The light beam is thereby directed towards the open end of the receiving optical fibre and coupled into this fibre. It is led along this fibre onto to the receiving photo detector, in this application usually a photodiode. This photodiode converts the intensity modulated light beam into a changing voltage over time, which is in its amplitude and frequency a representation of the movement of the diaphragm and therefore of the registered arriving sound wave.

This signal can then be further processed as any other audio signal. Founding on this very simple principle construction *Sennheiser* and the *Fraunhofer Institute for Applied Optics and Precision Engineering* in Jena, Germany started their development. In their detailed results they came up with the two following designs.

3.2.1. Fraunhofer Design

The *Fraunhofer Institute for Applied Optics and Precision Engineering* in Jena, Germany, applies the principle of a confocal defocusing sensor array[47] (fig. 8).

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[47] P. Schreiber: *Optisches Mikrofon* in *Fraunhofer IOF Jahresbericht 2003*, p. 84.

In the design of the *Fraunhofer Institute for Applied Optics and Precision Engineering* the light source, in this case a LED, transmits its light over an optical fibre towards the diaphragm. The light is then on exiting the sending fibre

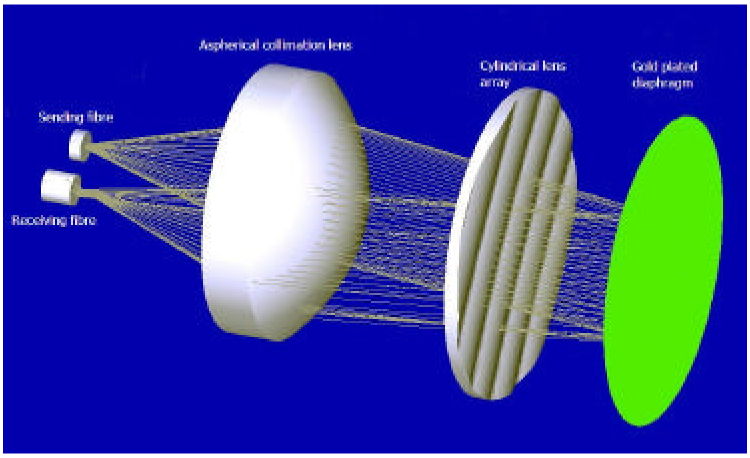

Figure 9 The confocal optical microphone

Figure 8 The optical microphone by the Fraunhofer Institute

collimated through an aspherical lens in order to focus the light beam and to control the scattering of the beam of light. Subsequently, the focussed light is passed through a cylindrical lens array that pinpoints the light onto the designated line-foci on the vacuum deposited gold plate on the inner side of the diaphragm. This results in the fact that not only the vibration in one single point is registered. The purpose of this design is the intent of the development team to take the possibility of partial diaphragm vibration into account[48].

The light, being reflected by the diaphragm, passes then through the lens array in reverse and is focussed thereby onto the receiving optical fibre. The modulation in intensity is produced in this set-up by tightening or loosening the focus of the returning beam of light in direct relation to the actual position of the diaphragm. This results in a higher intensity of light being coupled into the receiving optical fibre, as the focus is tighter, and less light is transmitted by the receiving fibre as the focus is loosened.

This modulated light is afterwards carried forward by the receiving optical fibre to the photo diode and converted into a corresponding voltage.

The following figure shows the frequency response of the laboratory demonstrator build by the *Fraunhofer Institute for Applied Optics and Precision Engineering* (fig. 10).

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[48] M. Feldmann: *Entwicklung eines optischen Mikrofons* on http://imt73.imt.ing.tu-bs.de/imt/institut/mitarb/feldmann/projekte/mikrofon, 29.11.2004.

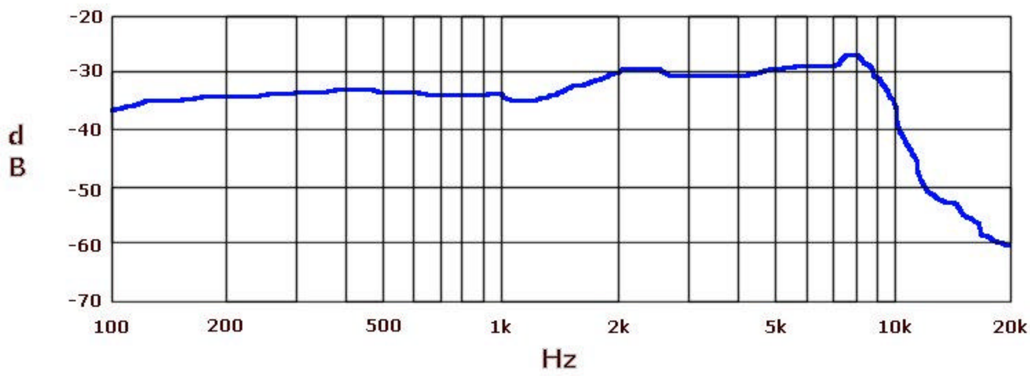

Figure 10 Frequency response of the confocal optical microphone without any response correction dampening in place.

This frequency response, especially as it is the untreated diaphragm, seems to be quite promising compared to the final and treated frequency response graph of a Shure SM58 (fig. 11), which until today is a microphone quite commonly used in live sound reinforcement.

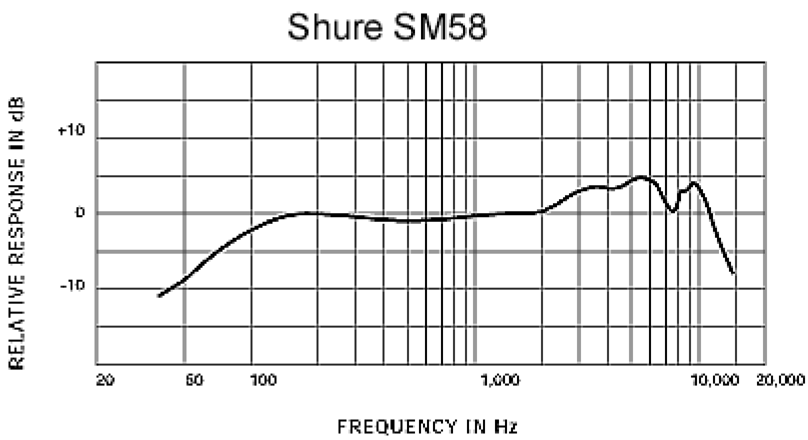

Figure 11 Frequency response of the Shure SM58

The obvious roll-off in the high frequency band, particularly above 10 kHz, is mostly due to the fact, that the inertia of the diaphragm becomes an issue. The assembly, trying to pay attention to the partial vibration of the diaphragm, has to rely on a quite large diaphragm diameter, usually above approximately 5 mm, in order to have enough reflecting area for the whole array of beams[49].

Another phenomenon, which is very closely related to this design, and again partially responsible for the high frequency roll-off, is the fact that above approximately 10 kHz the information gathered by the different focussing points starts to vary. Therefore, the fused light beams might not be representing the exact position of the diaphragm at that particular frequency[50]. Nevertheless, the design has the advantage that the correction of the frequency response is slightly easier to accomplish and the low amplitude impulse response tends to be slightly better compared to the other optical design, as the microphone is more sensitive to partial diaphragm vibrations[51].

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[49] P. Schreiber: *Optisches Mikrofon* in *Fraunhofer IOF Jahresbericht 2003*, p. 85.
[50] D. Garthe: *Ein rein optisches Mikrofon* in *Acoustica* Vol. 73, 1991, p75.
[51] C. B. Egbers: *Service Zeit: Optisches Mikrofon* on http://www.wdr.de/tv/service/technik/inhalt/20031113/b_3.phtml, 11.04.2005.

3.2.2. THE SENNHEISER DESIGN

Sennheiser even though relying on the same basic research findings takes a slightly different approach to the overall design of the optical microphone (fig. 12/13).

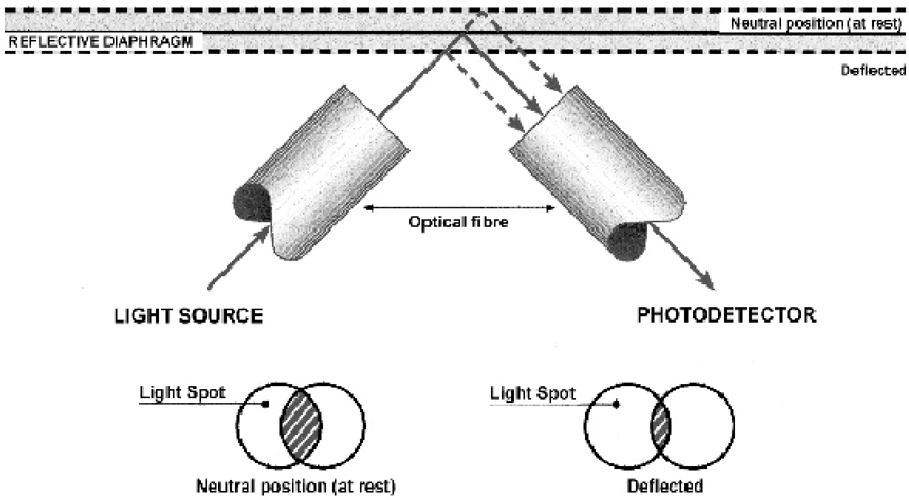

Figure 12 The image shifting optical microphone

In this design it becomes clear again that a focusing of the light is necessary since the scattering of the light beam on exiting the sending optical fibre is to grave to be ignored. Instead of using a lens array as the team of the *Fraunhofer Institute* does, *Sennheiser* tries to keep the assembly even more simple.

Sennheiser glued a half-spherical polymer lens directly to the open end of the sending optical fibre (fig. 14).

> "We were surprised that *Sennheiser* took this approach as it is, in our opinion, far more difficult to produce than our lens array"[52]

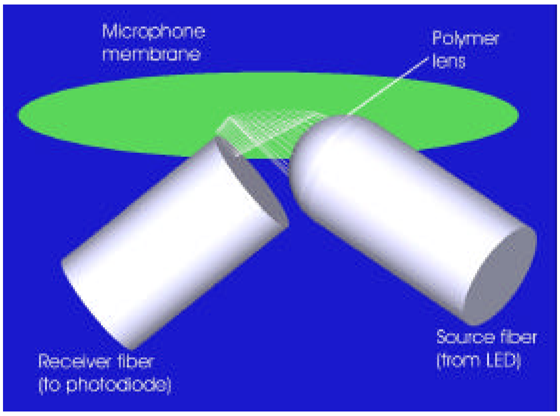

Figure 14 The image shifting design

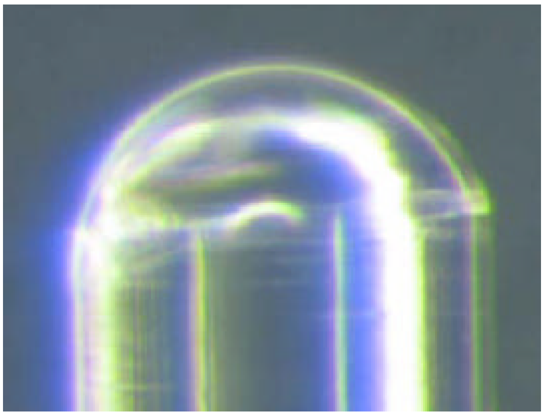

Figure 13 The polymeric lens on the sending fibre

[52] Dr. P. Schreiber, Fraunhofer Institute for Applied Optics and Precision Engineering in Jena, 02.11.2004.

This lens focuses the light beam on its exit of the optical fibre directly to one single point on the gold plated diaphragm. Therefore, a sharper focus of the light beam can be maintained until the re-entry of the light into the receiving fibre. This consequently results in a more linear change of the amount of light as the diaphragm is deflected by the arriving sound waves. Analogue to the *Fraunhofer* design, the amplitude modulated light is guided towards the photo detector and then converted into a changing voltage.

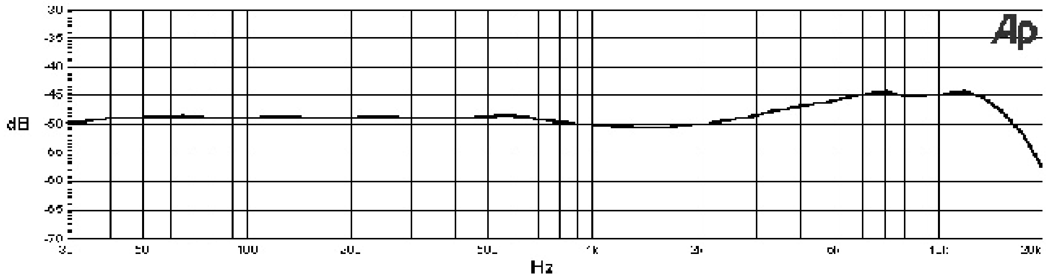

Figure 15 Frequency response of the image shifting design by Sennheiser.

The frequency response of the *Sennheiser* microphone version is over a broad bandwidth quite similar to that of the *Fraunhofer Institute*.

Main difference is the response in the high frequency band which is significantly better. This is due to the fact that, in contrast to the array of line-foci, as implemented in the confocal design, the image shifting design concentrates on one single spot on the microphone diaphragm. Ignoring the possibility of partial diaphragm vibration, which would possibly go unnoticed with this design, the diaphragm can potentially be constructed about 5 times smaller as in the confocal design[53]. This means in the region of

[53] P. Schreiber et al.: *Fiber-coupled optical Microphones*, AES116th Convention, Berlin 2004.

about 0.5 to 1 mm in diameter. At the same time this has of course a huge impact of the inertia of the diaphragm concerning impulse and high frequency response.

4. The Optical Microphone in Application

Imagine the possibilities emerging with a microphone which works completely without electromagnetic fields for the whole performing arts industry. Especially in live sound reinforcement the new microphone technology opens up possibilities in both the technical field and on the side of creative application and inventive handling.

4.1. Technical advantages

As already visualised in chapter two, telecommunication and with it electromagnetic pollution rises continuously and leads to more and more interference on microphones.

Even though it becomes common in cinemas, theatres and live concerts to post signs reminding the audience to switch of their mobile phones, this is understandably very difficult to control. Besides the fact that some people ignore these signs, overlook them or just forget about their mobile phones, others switch into vibration mode. Constant ringing during a performance is annoying and in classical concerts not at all tolerable, but the five to ten seconds of interference noise right before the ringing or alternatively vibrating, picked up over the microphone and reinforced through a PA is outrageous. Returning to the example from the DVD of the ringing mobile phone during the live interview:

Certainly the optical microphone would not have prevented the mobile phone from ringing and so have saved the interviewee from the embarrassing situation, but it would have been definitely less disturbing for the viewer without the interference noise. Still an average and at the moment a most of the times controllable problem, due to the fact that ringing mobiles need to be in close distance to the microphone to create electromagnetic interference, its risk will increase with the rising perception of communication devices.

A second problem in live sound reinforcement that can be easily solved by using optical microphones is radio frequency interference (RFI). RFI is, as is electromagnetic interference, an interference based on the principles of magnetic induction of electricity. As both of the prior mentioned 'traditional' microphone technologies operate more or less on the similar physical principles, they can inherently be influenced and heavily affected by these interferences.

> "The problems are not easily characterized, especially when the microphones are used in different environments. And RFI is a very mysterious phenomenon to deal with. You often have to proceed through trial-and-error. It's not as if you have an empty tire that you simply fill up with air. Shielding, noise cancelling, RFI chokes and capacitors and multi-directional devices are different solutions that may be appropriate in one situation but not in another."[54]

The optical microphone is in its design free of metal or other electro-conductive materials. It furthermore relies solely on optical means of detecting diaphragm movement; EMI and RFI, being electromagnetically based interferences, are not interfering with its operating principle. Therefore, the optical microphone is in its design inherently immune against EMI and RFI.

Electromagnetic interference and radio frequency interference leading to noise are yesterday's problems with the optical microphone.

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[54] Tocidlowski, S. in MRT „Improving microphone technology", on http://mrtmag.com/mag/radio_improving_microphone_technology , 08.04.2005.

4.2. Creative possibilities

The key requirement faced by most of the microphone manufacturers in the world of performing arts today is the demand for flexibility of a microphone.

Musical performers, actors and singers often wear head set microphones, which are in large scale performances necessary but most of the time should not be seen. Here again the optical microphone bears a clear advantage due to its flexibility in size. The optical microphone can be build almost 'infinitely' small. This possibility of miniaturisation is due to the fact that the diaphragm, especially in the *Sennheiser* design, as it is acting only as a mirror, can be quite small. In the mentioned *Sennheiser* design of an image shifting sensor, the diaphragm can even go down to a size of 0.5 mm in diameter, which is the smallest diameter needed for the microphone to work[55]. The microphone is smaller and therefore easier to hide with make up if necessary for the performance.

The optical microphone will open a whole new world to the performing arts community, as the design is resistant against any intrusion of water or humidity. Generally spoken, performers and musicians thickly covered in make-up sweating in the stage lights are let down by their microphone every second or third show on average[56].

The days of many generations of sound engineers and make-up artists being completely stressed out by the short circuiting of expensive microphones and successively their

[55] P. Schreiber et al.: *Fiber-coupled optical Microphones*, AES116th Convention, Berlin 2004.
[56] T. Zahn: *Staatstheater Nürnberg – Jahresbericht der Tontechnik*, p. 3.

replacement during a show are over. Even Britney Spears could possibly get through her show needing only one microphone instead of three or more microphones failing under the constant flow of sweat and water[57].

Being resistant against water does not only mean the microphone can not be destroyed by sweat or the beer glasses that are thrown on the stage by an ecstatic audience, but it also means a lot for the creativity of the performance. At long last the possibility for performances containing water is borne. Imagine Robbie Williams coming out under a water fall, wet to the skin the microphone the whole time in the hand or Britney Spears opening her show emerging from a giant aquarium like a mermaid.

But it could even go further: Already two decades ago the idea of an underwater music festival was born in the USA with the *Lower Keys Underwater Festival* that takes place once a year in early July. The unique event attracts more than 600 divers and snorkelers who gather each year for the sub-sea songfest showcasing a colourful diversity of marine life. The marine melodies range from the Beatles "Yellow Submarine" over Jimmy Buffett's "Fins" to the "Water Music" of Georg Friedrich Handel. While the music is broadcasted by the radio station WCNK and relayed down to the reef via *Lubell Laboratory* speakers suspended beneath boats, the festival makes always waves of its own too with string quartets, marching bands or snorkelling Elvis look-alikes playing under water guitar. Last

[57] M. Mann: *Tour Profile: Britney Spears in Europe* in: MIX on http://mixonline.com/mag/audio_tour_profile_britney, 11.04.2005.

year the *Key West Symphony Orchestra* played under the direction of their conductor Sabrina Maria Alfonso a submerged symphony as a twentieth anniversary special of the festival.

Figure 16 Lower Keys Underwater Festival

The festival is definitely one-of-a-kind and could be seconded only by a live concert under water that could also be broadcasted via radio. Here again the advantages of the optical microphone would come into full effect. Divers and snorkelers would not only watch the fancy dress of a long-haired mermaid with a harp and listen to music from tape, but musicians would be able to perform live. Certainly, even with an optical microphone the sound under water would sound strange and bubbly, but it would definitely be fun for the audience and support the idea of an underwater music festival.

4.3. CHALLENGES

Despite the before mentioned advantages of size, resistance against water, the inherent immunity against electromagnetic and radio frequency interference, and the figures concerning the frequency response the optical microphone is, being a new technology, unfortunately not a flawless miracle.

The main obstacle facing this young technology at the moment is the problem of self-noise of the whole optical microphone assembly. As it might be difficult to see, where noise could be generated as the whole microphone is based on optical principles and most people would consider light to be 'soundless', it might be necessary in order to fully understand the problem to return to the technical side again for a brief excursus:

Returning to the basic principle of the optical microphone (fig. 17), four general areas of noise infliction can be identified. These areas are: The light source, the optical fibre, the transducer itself, and the photo detector[58]. Laboratory analysis revealed that the inflicted noise of the fibres is negligible up to nearly 600 to 1000m of cable length and can

[58] D. Garthe: *Faser- und integriertoptische Mikrofone auf der Basis intensitätsmodulierender Membran-abtastung*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 214, p. 22.

therefore be ignored[59]. The same is true for the noise generation of the transducer assembly[60].

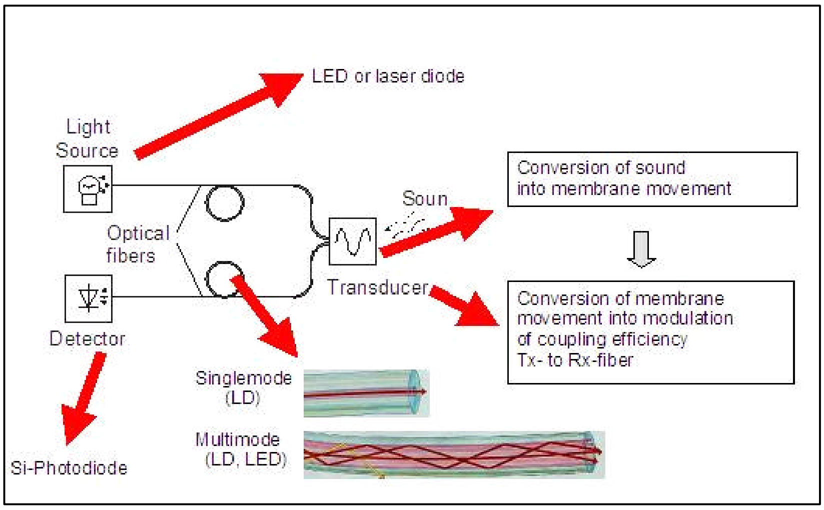

Figure 17 Schematic of the optical microphone

These results leave two possible sources of noise infliction that need to be taken into consideration: The light source and the light receiver.

Concerning the light source it has to be distinguished between the two possible types of light sources applied in the optical microphone[61]. The first is the Laser diode (LD). Main advantage is the high possible output power and the ease of effectively guide this beam of

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[59] Y. Kahana, A. Paritsky, A. Kots, S. Mican: *[N488] Recent advances in optical microphone technology*, International Congress and Exposition on Noise Control Engineering, Seogwipo (Korea) 2003.
[60] P. Schreiber et al.: *Fiber-coupled optical Microphones*, AES116th Convention, Berlin 2004.
[61] P. Schreiber: *Optisches Mikrofon* in *Fraunhofer IOF Jahresbericht 2003*, p.85.

light towards the reflective diaphragm[62]. Problematic in this layout is the fact that, as laser light is one single coherent light wave, very much as a single sine wave in audio, the cycle of the light generating oscillator is detectable as a change in intensity through the receiving photo detector[63]. Therefore, this change results in the generation of noise. The option of combating this effect by creating a reference signal in order to eliminate the oscillator noise, even though possible, has proven to be very difficult, unreliable and extremely expensive, and has therefore been abandoned[64]. This leads to the second light source, the light emitting diode or LED, being predominantly used in the development of the optical microphone. Apart from being cheaper it also generates a random beam of light[65], avoiding therefore any infliction of noise generated by the light source, as the intensity of the light is much more stable compared to the LD[66].

The last source of noise in the design of the optical microphone is the photo detector. Concerning this source of noise the possibilities of compensating are rather limited[67]. Unfortunately, this part of the whole assembly, during the initial testing phase, turned out

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[62] E. Udd: *Light Sources* in *Fiber Optic Sensors, An Introduction for Engineers and Scientists* edited by E. Udd, 1991, p. 37-68.
[63] D. Garthe: *Ein rein optisches Mikrofon* in *Acoustica* Vol. 73, p. 76.
[64] H. Heinrich: *Stabilisierte Laserlichtquelle mit Rauschunterdrückung für den Betrieb eines intensitätmodulierenden optischen Mikrofons*, Studienarbeit 2641EA, p. 43.
[65] D. Garthe: *Faser- und integriertoptische Mikrofone auf der Basis intensitätsmodulierender Membran-abtastung*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 214, p. 23.
[66] P. Schreiber et al.: *Fiber-coupled optical Microphones*, AES116th Convention, Berlin 2004.
[67] D. Garthe: *Faser- und integriertoptische Mikrofone auf der Basis intensitätsmodulierender Membran-abtastung*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 214, p. 32.

to be the predominant noise source[68]. This is mostly due to the internal design of the standard photodiode[69] and is therefore a disadvantage, until the development in this field of science has progressed further[70], the designers and in succession the end-user will have to live with for the time being. Due to the world-wide concentration on regenerative energy sources such as sunlight, a significant step forward in the development is immanent[71]. Successively the optical microphone technology will develop accordingly.

Returning to the direct application of the optical microphone, this self-generated noise results in a slightly less good signal-to-noise ratio of the optical microphone at this time compared with the traditional' microphone technologies. In figures this actually means that the optical microphone is described with a signal-to-noise ratio of around 63 to 60dB[72]. This is not an ideal figure but it is a starting point especially when compared to the Neumann U87Ai, which is rated around 69dB dependent on the polar pattern[73] or more generally when set into relation with the statement of the Georg Neumann GmbH

68 R. H. Hamstra, P. Wendland: *Noise and Frequency Response of Silicon Photodiode Operational Amplifier Combination* in Appl. Opt. 11 Nr. 7, p. 1541.
69 R. Mueller: *Rauschen*, Halbleiterelektronik Bd. 15, p. 5.
70 D. Garthe: *Faser- und integriertoptische Mikrofone auf der Basis intensitätsmodulierender Membran-abtastung*, Fortschrittsberichte VDI Reihe 10: Informatik/Kommunikationstechnik Nr. 214, p. 102ff.
71 N. Lossau: *3D-Kamera erfasst ihr räumliches Umfeld in Echtzeit* in: Die Welt online, 09.04.2005 on http://www.welt.de/data/2005/04/09/670769.html, 11.04.2005.
72 Phone-or Ltd.: *Fiber Optical Microphone for remote monitoring in indoor applications requiring RFI/EMI immunity* on http://www.phone-or.com/temp/data/FOM_MON1_Datasheet.pdf, 09.04.2005.
73 Georg Neumann GmbH: *Technical Data U87Ai (mt)* on http://www.neumann.com/infopool/mics/produkte.php?ProdID=u87ai, 09.04.2005.

that studio condenser microphone should have a signal to noise ratio of 74 to 64 dB[74]. As even these figures are not so far off in comparison to studio microphones, it remains open if these signal-to-noise-ratio figures of the optical microphone in the application of live sound reinforcement are inflicting a critical problem.

[74] Georg Neumann GmbH: *Glossary for technical Parameters* on http://www.neumann.com/infopool/mics/glossary/gloss11.htm, 09.04.2005.

5. CONCLUSION

The optical microphone as a new approach in technology constitutes the first new turn in the development of microphone technology in nearly a century. With its advantages in the field of resilience against water and its immunity against interference it opens up a whole new world of technical and creative possibilities for the performing arts industry.

The majority of the impact of this revolutionary technology definitely manifests itself in live sound reinforcement. Contrary, to the side of studio engineering where a mistake can more easily be corrected as the engineer has the luxury of a second chance, the field of live sound reinforcement is not as forgiving. Live sound reinforcement is undeniably a field where second chances are rather sparse. Therefore, the avoidance of mistakes and possible hazards is usually the highest priority. A microphone technology such as the optical microphone with its described advantages concerning humidity and interference can be in this context a pristine method of excluding possible problems and annoyances well in advance. In the stressful environment of live sound reinforcement this means one thing less to constantly think about and leaves more space to pay attention to the creative side of a performance.

But even outside the classical sound technology the optical microphone bears undeniable advantages and has revolutionary impact. Due to its lack of any electric and magnetic elements and its stability in extreme temperatures, the optical microphone is suitable for monitoring sound in harsh environments, electrical utilities, oil and gas detection and explosive areas. The Israeli company *phon-or* develops optical microphones especially for these purposes as well as for surveillance, due to the fact that the microphone is inherently tape-proof. Another important field for the optical microphone is medicine technology. Until now there was no possibility for medics to communicate with their patients during a magnetic resonance imaging. The electromagnetic field of the magnetic resonance tomograph interfered with the microphones. The optical microphone changes this completely and the first magnetic resonance tomographs using optical microphones for communication are already built.

Returning to sound technology, the optical microphone is still in its fledging state. Problems occur at this time in the mass production as the set-up is relying on an enormously precise assembly. Therefore, the only existing specimens of the optical microphone for live sound application are the prototypes build by the developers themselves. A thorough testing under 'real live' conditions poses therefore still a big challenge for the future, as so far only tests in the secure environment of laboratory conditions have been performed. Understandably, due to this production state the microphone is today still a very expensive solution to the growing problems of interference in live sound reinforcement. However, as described in the last chapter, the results of these laboratory tests are quite promising and permit good faith for the tests to follow under 'real life' conditions in the very near future.

Even though the time might not have already come for this revolutionary new technology of the optical microphone, it is apparent that in the future the possibilities and occasions for the application of the optical microphone will arise. To break new ground in technology is sometimes very difficult and new technologies face teething troubles as well as many prejudices. Sometimes, they are just a little ahead of the times. This all might be true for the optical microphone and its application in sound technology but it is apparent that changed surrounding conditions as the ever growing electromagnetic pollution will force sound technology to take measures in the near future.

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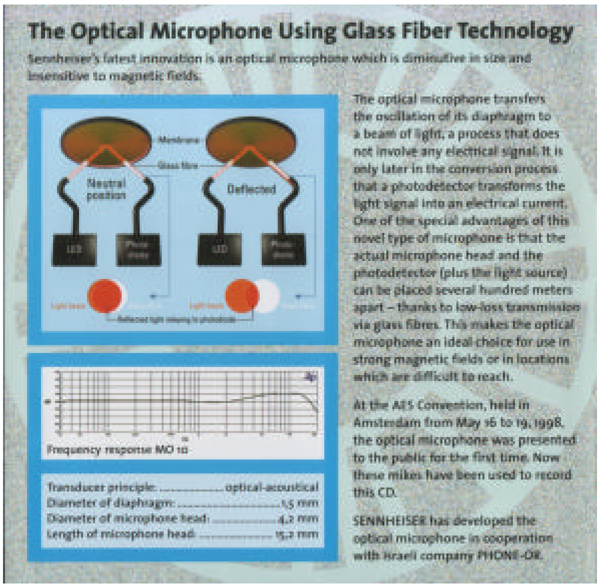

1. Hungarian Dance No. 5 ....Johannes Brahms
2. Wien bleibt Wien ....Johannes Schrammel
3. Bolero ....Carl Bohm
4. Tik Tak Polka ....Johann Strauss
5. Radetzky March ....Johann Strauss (father)

Performed by:

The Soloists of the Johann-Strauss-Orchester

Conducted by:

István Szentpáli

Recorded by:

Das Emil Berliner Haus, Klaus Hiemann, Stefan Shibatz

At the Markuskirche Hannover

APPENDIX B – EXAMPLES DVD

1. WDR Lokalzeit Interview (Video Example)

   recorded from TVTotal 07.04.2005.

2. Recording with noise from a mobile phone relay station (Audio Example)

   recorded at The Projection Rooms, Liverpool.