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Microwaves in fire detection

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Abstract

In this contribution the issue of fire detection by means of thermal radiation in the microwave region of the electromagnetic spectrum is addressed. The aim of this work is to show that microwave radiation is a useful quantity to detect fires, which is confirmed by measurements. Some of the results even indicate that it could be possible to detect smoldering fires with microwaves earlier than with smoke or with gas detectors.

The first part is a short summary of the basic concept of our previous paper [Kaiser T, Kempka T. Is microwave radiation useful for fire detection? Proceedings of 12th international conference on automatic fire detection AUBE ’01, vol. 965, 26–28 March 2001. Gaithersburg: NIST Special Publication; 2001.] published at AUBE ‘01, along with a short revisit of the physical fundamentals of thermal radiation, of electromagnetic wave propagation, and of attenuation.

In the second part, the microwave receiver will be presented, which is used to conduct experiments in Duisburg’s fire detection lab. The receiver is able to measure thermal radiation in the frequency region from 2 to 40 GHz, and the superheterodyne technique used by the receiver enables a rather flexible measurement range among arbitrary frequency bands with individual widths of 100 MHz. The receiver is controlled by a normal PC, which makes the measurement setup configurable, i.e. one can choose any combination of 380 × 100 MHz frequency bands for a single measurement.

Some measurement results for the standardized European test fires TF1 and TF2 according to ISO 7240 (EN 54 Part 9) are shown in the last part of this contribution. The gathered data is discussed and compared to ionization chamber (MIC), to extinction light sensor (MIREX), and to gas-concentration measurements.

Keywords: Fire physics; Fire detection; Microwaves

1. Introduction

Typical imaging cameras and optically-based smoke and flame detectors utilizes thermal radiation in the infrared (IR) region. IR radiation is in the wavelength range $750\,\mathrm{nm} \leqslant \lambda_{\mathrm{IR}} \leqslant 1\,\mathrm{mm}$. The question arises whether electromagnetic radiation with other wavelengths λ can be used for fire detection as well. Without a doubt, most of the thermal power radiated by a fire exists in the IR spectrum. Thus, the first choice for a *radiometer*, a device that measures the radiated power of a fire, is the IR spectrum. Examples of such radiometers are flame detectors [1] and the aforementioned IR cameras. From scattered light or light extinction detectors, however, we know that the attenuation of IR radiation due to smoke is rather high. In fact, those detectors *exploit* the high attenuation of smoke or the high scattering due to smoke in the fire case and *not* the emitted radiation power of the fire. This intuitively suggests investigating a region of the electromagnetic spectrum where the attenuation is less than in the IR region although the emitted power in those regions is even lower. Two such regions of investigation are the micro- and millimeterwave regions, which include the wavelength range of $1\,\mathrm{mm} \leqslant \lambda_{\mathrm{MW}} \leqslant 187\,\mathrm{mm}$ or the corresponding frequency range $1.6\,\mathrm{GHz} \leqslant f_{\mathrm{MW}} \leqslant 300\,\mathrm{GHz}$. Hence, exploiting thermal radiation in the microwave (MW) region for fire detection purposes is the topic of this contribution.

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Nomenclature

A	surface of radiating body
$A_e(f)$	effective antenna area
c_0	speed of light in vacuum
d	distance between fire and antenna
d_p	smoke particle diameter
F	noise figure
F_r	receiver noise figure in db
f	frequency
f_c	center frequency
G	gain
G_{dB}	gain in dB
G_{MR}	receiver amplification
$G(f)$	antenna gain
h	Planck's constant
$I(\lambda)$	scattered intensity
k	Boltzmann constant
n	sampling index
$P_F(f,T)$	emitted radiation power of fire
$P_R(f,T)$	received radiation power
T	temperature
T_1, T_2	duration within receiver
T_r	receiver noise temperature
t	time
$w_E(f,T)$	emissivity

Greek symbols

Δf	bandwidth
ΔP_m	receiver power resolution
ΔT_m	receiver temperature resolution
λ	wavelength
τ	duration of measurement

2. Concept

Fig. 1 introduces the concept of microwave fire detection. Every physical body with a temperature above absolute zero emits thermal radiation. The amount of radiation is dependent upon the body temperature T and emissivity $w_E(f,T)$, where $w_E(f,T)$ is a material property with

$$0 \leqslant w_E(f,T) \leqslant 1 \quad \forall f, T.$$

Bodies with $w_E(f,T)=1$ are called black bodies. For a black body the thermal radiation power is directly proportional to T^4. Non-black bodies emit lesser power than black bodies at the same temperature. Thus, the black body radiation is an upper bound for the thermal radiation power at each temperature. If the radiation is measured within a room at thermal equilibrium, the power is less than or equal to the power of a black body at room temperature. If a fire is starting, i.e. if there is a body with increasing temperature, the radiation power $P_F(f,T)$ of this body increases also, and it will exceed the power of the surroundings at a certain fire temperature, even if there are differences in emissivity between the fire and the surroundings. Consequently, the idea is to measure the power of the thermal radiation $P_R(f,T)$ within a room in order to detect fires by an increase in power.

In order to quantitatively discuss this simple concept, the thermal radiation power of a fire $P_F(f,T)$ and the received radiation power $P_R(f,T)$ must be known to some extent. The propagation of electromagnetic waves and their interaction have to be taken into account, because they impact $P_R(f,T)$.

Fortunately, all of these phenomena are well understood. Planck's law [2,3] of radiation gives an upper bound for the thermal radiation power of a fire. For propagation effects—without attenuation due to smoke—we can apply the simplistic free space propagation model (known e.g. from wireless communications). The interaction with matter accounts for the attenuation due to smoke, and it is described by Mie-theory and Rayleigh-scattering. In the following paragraphs these physical fundamentals are briefly revisited [2,3].

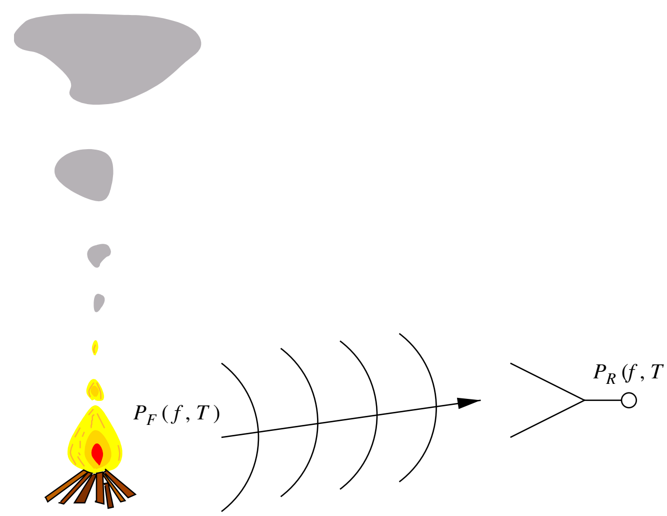

Fig. 1. Concept.

The thermal radiation power of the fire $P_F(f,T)$ can be calculated from the Rayleigh–Jeans-law and the emissivity $w_E(f,T)$. The Rayleigh–Jeans-law is an approximation of Planck's law in the microwave region, which describes the thermal radiation power of a black body. The Rayleigh–Jeans-law is valid for $f \ll k/h \times T \approx 2 \times 10^{10}\,\mathrm{Hz/K} \times T$, so this approximation is useful at a maximum of $f \approx 60\,\mathrm{GHz}$ for room temperature (300 K). It holds

$$\mathrm{d}P_F(f,T) = \frac{2AkT}{c_0^2}\, w_E(f,T) f^2\, \mathrm{d}f, \tag{1}$$

with BOLTZMANN constant k, speed of light in vacuum c_0, and surface area and temperature of the fire, A and T, respectively. For the received power $P_R(f,T)$ at the antenna it follows that under free space propagation [3–5],

$$dP_R(f,T) = \frac{A_e(f)}{4\pi d^2}\, dP_F(f,T), \quad (2)$$

where d is the distance between fire and antenna, $A_e(f)$ is the effective area of antenna, and $G(f) = A_e(f)f^2/c_0^2$ is the antenna gain. Assuming that the emissivity $w_E(f,T)$ and the antenna parameters $A_e(f)$ and $G(f)$ are constant within a narrow frequency band with center frequency f_c and bandwidth Δf, we obtain

$$P_R(f_c, \Delta f, T) = \frac{2kAT}{c_0^2 d^2}\, w_E(f_c,T)A_e(f_c)f_c^2\Delta f = \frac{kAT}{2\pi d^2}\, w_E(f_c,T)G(f_c)\Delta f. \quad (3)$$

This equation is used to calculate the received thermal radiation power within a frequency band for all possible bodies, including gases, if the emissivities for these bodies are known; however, there is little published information about $w_E(f,T)$ for microwave frequencies, especially for burning materials. Thus, Eq. (3) can be used mainly to calculate the upper bound of this radiation. Real measurements of the received power are still necessary to validate the functionality of this approach.

Beside the received power, the attenuation of the thermal radiation by smoke or by other matter is of relevance as well. Since thermal radiation is an electromagnetic wave, the attenuation of electromagnetic waves by dielectric particles is crucial.

Two effects are included, absorption of energy by particles and scattering of energy by particles. Both effects lead to attenuation or to extinction of the incident electromagnetic wave. The general solution to this problem is given by MIE and is known as MIE-theory or MIE-scattering [6]. MIE assumed that the dielectric particles are spheres with a fixed diameter d_p and that the collisions are elastic, i.e. the kinetic energy remains unchanged. The approximation for particles that are small compared to the wavelength λ of the incident wave is called RAYLEIGH-scattering, which is valid for [6]

$$\frac{d_p}{\lambda} < \frac{1}{10}.$$

The particle size distributions of smoke in fires are in the range [7] of 4.2 nm–7.5 μm. The wavelength of microwaves varies between $1\,\text{mm} < \lambda < 187\,\text{mm}$, so the maximum ratio is

$$\left(\frac{d_p}{\lambda}\right)_{max} = 0.0075.$$

Hence, RAYLEIGH-scattering is reasonable, and the scattered intensity $I(\lambda)$ is strongly dependent on the wavelength λ, in this case to λ^{-4}. Thus, for the comparatively long wavelengths ($\lambda_{MW} \geqslant 1\,\text{mm}$) in the microwave region in contrast to the IR region, this scattering is quite small and hence negligible. This is one distinct advantage when using the microwave region of the spectrum for fire detection.

This result depends on the aforementioned MIE-assumptions, which are valid for smoke of smoldering fires but not for smoke of open fires. However, the measured scattered intensity for smoke of open fires is less than the scattered intensity for smoldering fires [8], so RAYLEIGH-scattering is reasonable to estimate the upper bound of the scattered intensity.

3. Microwave receiver

This section describes the microwave receiver constructed to measure the thermal radiation power of fires in the range of 2–40 GHz. The receiver is designed according to the superheterodyne principle like a radio receiver, so the receiver can be tuned to any 100 MHz broad frequency band in the 2–40 GHz frequency range. It also allows the complete frequency range to be split into two front-ends, one front-end for the frequency range of 2–26 GHz and the other front-end for the frequency range of 26–40 GHz. Fig. 2 shows the principle of this receiver.

The four broad-band antennas cover the frequency bands 2–12, 12–18, 18–26, and 26–40 GHz and are followed by a switching stage, where each of the antennas or a "Hot Load" could be selected. The Hot Load with a constant temperature of 100 °C is used to calibrate the complete measurement device. After the switching stage two low noise amplifiers (LNA)—one in each front-end—amplify the received thermal radiation power with a gain of $G_{dB} = 30\,\text{dB}$ and a noise figure F less than 3 dB over the whole frequency range. The low noise figure F of the LNAs is needed to achieve a satisfactory temperature resolution ΔT_m. The mixers of the next stage shift the input signal to the intermediate frequency $f_{IF} = 150\,\text{MHz}$ and limit the bandwidth to $\Delta f = 100\,\text{MHz}$. A local oscillator generates the mixing frequency f_{LO} for the mixers. The desired measuring band is chosen by tuning this oscillator. The mixers are followed by further amplifiers and a second switching stage is used to select one of the two front-ends. Before the thermal power is measured with a conventional power meter, it is further amplified by 60 dB at the intermediate frequency f_{IF}. A data acquisition and control computer collects the measurement data of the power meter. It controls all the switching as well as the local oscillator. It is connected via the general purpose interface bus (GPIB).

The temperature resolution of this receiver can be estimated with the so called *radiometer formula* [3,5,9]:

$$\Delta T_m = \frac{T_m + T_r}{\sqrt{\Delta f \tau}},$$

with the radiometer bandwidth Δf, the measurement time τ, the equivalent temperature of the measured object T_m, and the receiver noise temperature T_r.

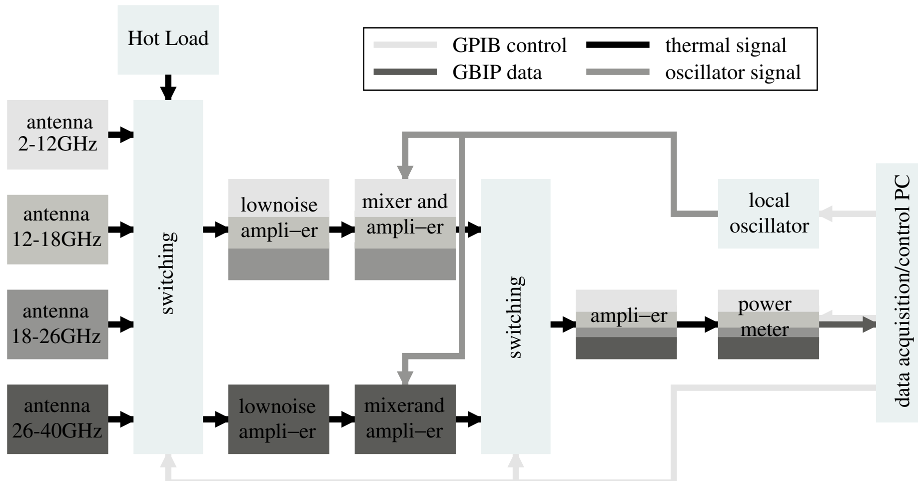

Fig. 2. Schematic diagram of the microwave receiver.

The measurement time τ is limited to a few seconds, because the receiver should be able to track the variation of the thermal radiation of a starting fire. In this receiver τ can be chosen as $\tau = n \times 25\,\text{ms}$ where $n \in \mathbb{N}$.

The receiver noise temperature T_r could be expressed [10,11] by the receiver noise figure F_r

$$T_r = (10^{(0.1 \cdot F_r)} - 1) \times 290\,\text{K}.$$

For the noise figure of concatenated systems holds [11,12]

$$F_g = F_1 + \frac{F_2 - 1}{G_1} + \cdots + \frac{F_n - 1}{G_1 \cdot G_2 \ldots G_n} = F_1 + \sum_{v=2}^{n} \frac{F_v - 1}{\prod_{\mu=1}^{v-1} G_\mu}, \quad F_v \geqslant 1,\ G_\mu > 0,$$

where G_μ is the gain of the μth system. From this it follows that the receiver noise figure F_r is dominated by the noise figure F_1 of the first subsystem, which is the LNA in each front-end of this receiver. Furthermore, the noise figures of the succeeding stages—mixers and amplifiers—that follow the LNA-stage are not so important, because they are divided by the gain of the LNAs, which is equal to 30 dB ($G_1 = 1000$). So $F_r = 3\,\text{dB}$ is used for the estimation of the resolution of the receiver. This results in a receiver noise temperature of $T_r = 290\,\text{K}$. The relation between the equivalent temperature (T_r, T_m) and the corresponding power is given in general by [3,5,11]

$$P = k \times \Delta f \times T.$$

Table 1represents some typical values for the temperature resolution ΔT_m and for the power resolution $\Delta P_m = k \times \Delta f \times \Delta T_m$ of this microwave receiver.

Some limitations of our microwave receiver should be mentioned also.

In the following, the measured thermal radiation power $P_M(f, T) = G_{MR}(f) \times P_R(f, T)$ is presented, which is equal to the power $P_R(f, T)$ at the receiver multiplied by the total amplification $G_{MR}(f)$ of the receiver, where $P_R(f, T)$ can be estimated by Eq. (3). The calibration of the receiver accounts for time-dependent deviations of $G_{MR}(f)$, but it is not an absolute value calibration for $P_M(f, T)$, i.e. the receiver is useful as a relative measuring device that compares the measured thermal radiation power $P_M(f, T)$ of fire to the non-fire situations for each frequency band, respectively. The evaluation of the absolute value of $P_M(f, T)$ requires further calibration efforts and will not be discussed here.

Table 1
Temperature and power resolution of the microwave receiver

T_m (K)	300	600	1000	1500	2000
P_m (pW)	0,4	0,8	1,4	2,1	2,8
ΔT_m (K)	0,2	0,6	0,8	1,1	1,4
ΔP_m (aW)	0,3	0,8	1,1	1,5	1,9

Another drawback is the rather complex control of the receiver, which follows from the broadband setup. Because of this, the duration between two consecutive measured values within one frequency band vary for each different measurement configuration. For each configuration one sample will be measured in the first frequency band. Then the receiver changes to the next frequency band and takes another sample. After all the selected frequency bands are measured, the receiver will measure the first band again. The duration T_1 of switching to another frequency band depends on the switching times for the different switches and on the settling time of the local oscillator. The time T_2 between two consecutive measurements in the same frequency band depends on the number of measured bands, and this can take a few seconds. This is the reason why measurement results (see next section) for multiple frequency bands are drawn over the sample number instead of time.

In the next section, results from measurements conducted in Duisburg's fire detection lab are presented in order to gain more insight about microwave emission of fires.

4. Experiments

In this section some fire test results are presented. The distance between the receiver and the fire was approximately 1 m for all experiments. This distance is used because the emitted thermal radiation should be affected by the propagation of the thermal radiation as little as possible. The influence of the distance between the receiver and the fire is not addressed here, because more theory on antennas—like antenna patterns—is necessary to discuss this issue. The test fires TF1 and TF2 from the European standard [13] EN 54 Part 9 (old version) are used for the measurements.

TF1 is an open wood fire where beechwood is burned. Fig. 3 presents the measured thermal radiation power $P_M(f, T)$ of this fire for different frequencies. The ignition of the wood took place at about $n = 30$ samples, and it is marked by the dashed line. At about $n = 100$ samples, the measured power begins to rise in a nearly exponential manner until it reaches a maximum at approximately $n = 150$ samples. After that time, the radiation power decreases linearly. A receiver calibration took place at about $n = 280$ samples. Therefore the power of the ''Hot Load'' was measured instead of the fire power, which is set to zero. The two jumps between $n = 400$ and 500 follow from removing the remaining wood from the observed area. This measurement was done for the frequency range of 26–40 GHz. The results of the other frequency bands within this range are very similar, so they will not be shown here. The time difference between two samples n was about 3.5 s for this experiment, but in order to get an impression of the time behavior, a measurement for a single frequency band (center frequency $f_c = 33.75$ GHz) was performed.

The result of this measurement is depicted in Fig. 4. The fire was ignited at 240 s, which directly led to a small peak in the measured thermal radiation power $P_M(f, T)$. The reason for this peak is possibly related to the automatic ignition method that was used, where guncotton is electrically heated until it ignites.

A rise in the measured power can be observed at about 330 s. Hence, 90 s after ignition, changes in the measured radiation power become visible, which is in agreement with data taken from MIC, MIREX, CO-, and CO_2-measurements.

The same measurements were performed for TF2, which is a smoldering wood fire. The beechwood was placed upon a heater, which was heated to 600 °C.

The frequency range of 26–40 GHz was considered again. Because the results are very similar in the different frequency bands, only the time-dependent measurement for the center frequency $f_c = 31.75$ GHz is shown in Fig. 5.

The heater was switched on 120 s after the beginning. At 200 s the received thermal radiation power $P_M(f, T)$ began to rise. This is a much faster reaction than MIC, MIREX, CO-, and CO_2-measurements show. In these measurements it takes about 360 s before changes are observable, because the wood sticks must heat up to a certain temperature until they start to produce smoke. (Fig. 6 represents normalized MIC, MIREX, CO-, and CO_2-measurements for convenience.) The maximum is reached at 800 s, and it is followed by a smooth decline. In the end, at about 1700 s the remaining wood is removed from the observed area. The jump in thermal radiation can be seen very clearly, although there was little wood remaining after pyrolysis.

The last figure represents measurements of TF2 within the same frequency range for a different measuring setup. This time there was a tile of the mineral fibre ceiling placed between the microwave receiver and the fire. The tile has a thickness of 2 cm, and it covered the antenna completely. Hence, the fire was observed *through* an artificial ceiling. Comparing Fig. 7 to data recorded without the tile shows

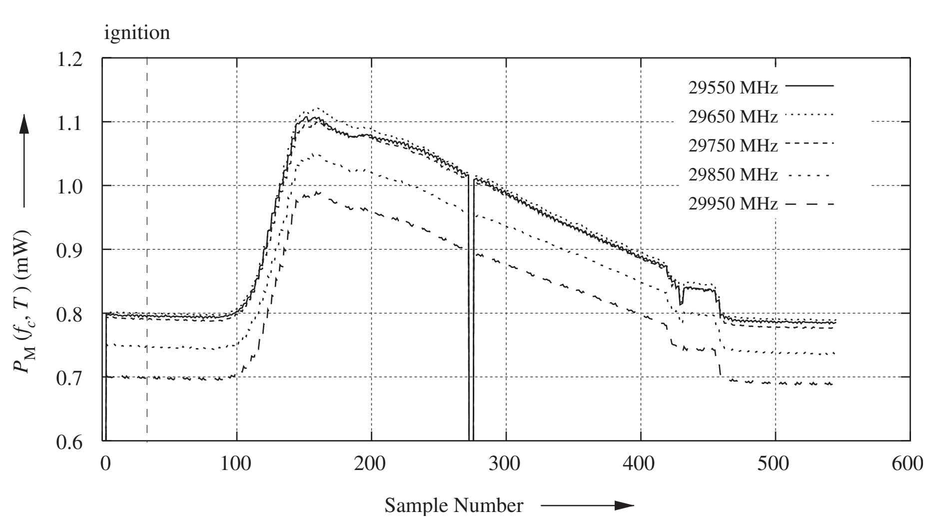

Fig. 3. Measured thermal radiation power $P_M(f, T)$ of a TF1 for different frequencies. Time between samples: 3.5 s.

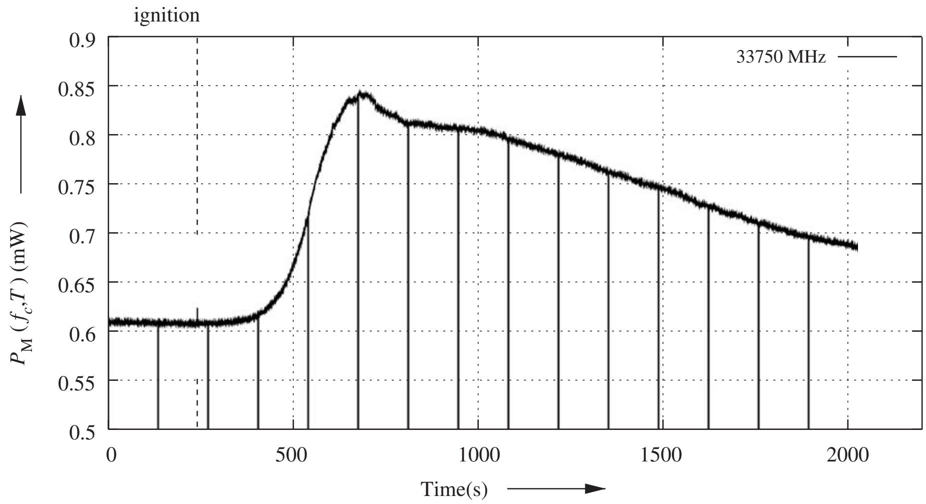

Fig. 4. Measured thermal radiation power $P_M(f, T)$ of a TF1.

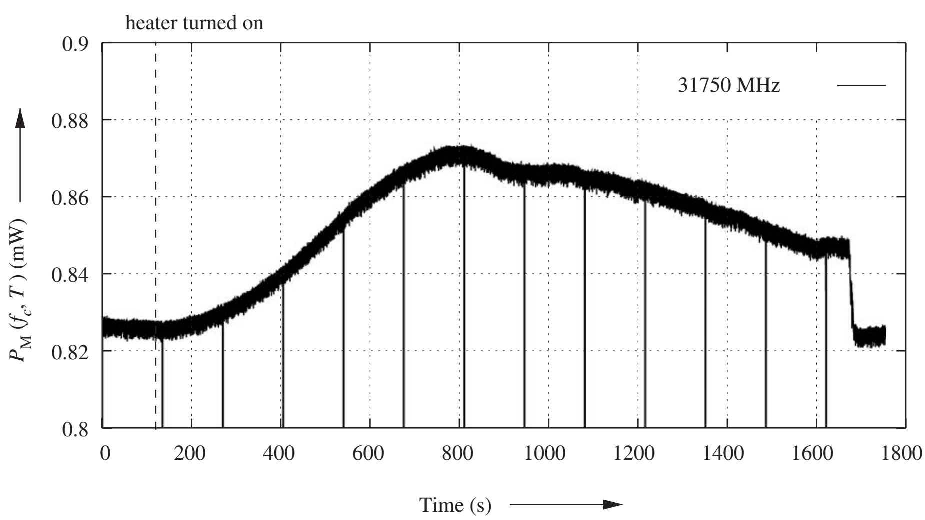

Fig. 5. Measured thermal radiation power $P_M(f, T)$ of a TF2.

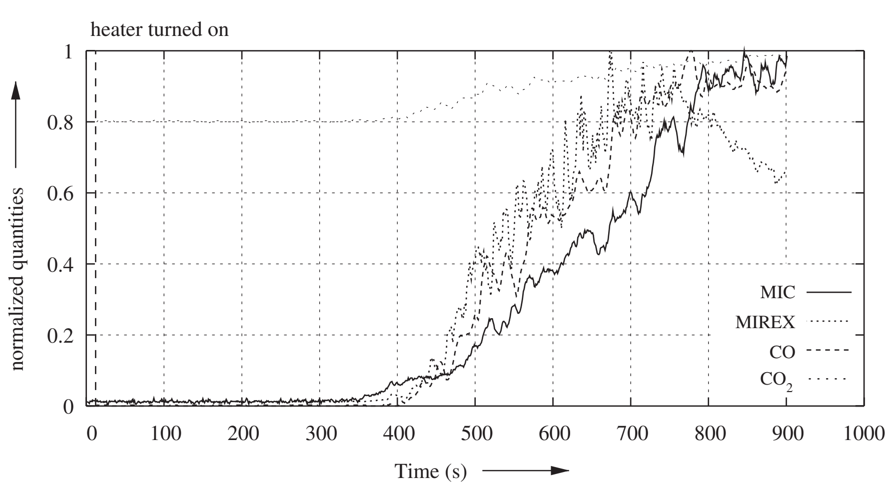

Fig. 6. Normalized MIC, MIREX, CO-, and CO_2-measurements of a TF2.

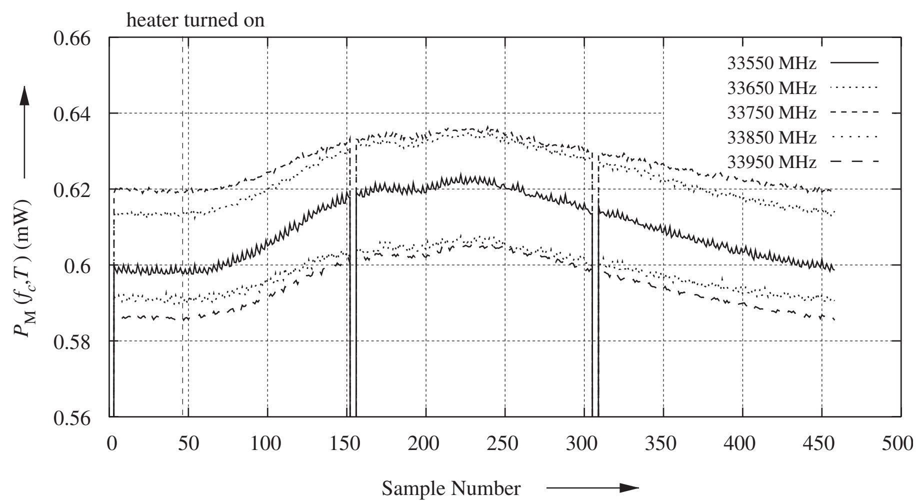

Fig. 7. Measured radiation power $P_M(f,T)$ of a TF2 behind ceiling tile.

that the curves are very similar to each other at a first glance; however, there are some slight differences. The reaction time is about 33% longer, which yields to a reaction time of about 120 s if the tile is present, and the maximum is approximately 33% lower. In general, however, the fire is still detectable from the measured data. Note that this relevant observation is only based on a measurement bandwidth of 100 MHz, i.e. by averaging over frequency the signal to noise ratio can be further improved.

5. Conclusion

The idea of using microwaves for fire detection along with the underlying physical theory was presented at the AUBE '01 conference [14]. This contribution presents a receiver for thermal radiation in the microwave region of the electromagnetic spectrum. Data taken from two European standardized test fires confirm the basic functionality of this approach. Hence, thermal microwave radiation is a measurable quantity to detect fires. The measurements of TF2 indicate that in some cases it is possible to detected fires earlier than with optical- or gas-sensors. A further advantage is the penetration of non-metal materials by microwaves, which allows detection even behind walls. Future aim is to extend these measurements to other fire and non-fire-situations. The usage of the complete frequency range of the receiver will also be considered.

Acknowledgment

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