Improving the Signal Visibility of Optical-Disk-Drive Sensors by Analyte Patterning and Frequency-Domain Analysis

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Abstract. One limitation of using compact disks (CDs) and optical disk drives for sensing and imaging of analytes placed on a CD is the fluctuations in the voltage signal from the disk drive generated while reading the data on the CD. In this study, we develop a simple, low-cost strategy for sensing and identification using CDs and optical disk drives that spectrally separates contributions to the voltage signal caused by an analyte intentionally placed onto the CD and that caused by the underlying data on the CD. Analytes are printed onto a CD surface with fixed spatial periodicity. As the laser beam in an optical disk drive scans over the section of the CD containing the analyte pattern, the intensity of the laser beam incident onto the photodiode integrated into the disk drive is modulated at a frequency dependent on the spatial periodicity of the analyte pattern and the speed of the optical disk drive motor. Fourier transformation of the voltage signal from the optical disk drive yields peaks in the frequency spectrum with amplitudes and locations that enable analyte sensing and identification, respectively. We study the influence of analyte area coverage, pattern periodicity, and CD rotational frequency on the peaks in the frequency spectrum associated with the patterned analyte. We apply this technique to discriminate differently-colored analytes, perform trigger-free detection of multiple analytes distributed on a single CD, and detect at least two different, overlapped analyte patterns on a single CD. The extension of this technique for sensing and identification of colorimetric chemical reagents is discussed.

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1. Introduction

Optical disk technology was developed in the late 1970s and has since become a widely-used and comparatively-inexpensive form of portable data storage and data reading. The electronic circuitry and excellent focussing optics within optical disk drives are ideally suited for the development of low-cost optical metrology and sensing applications [1]. Several publications have described the adaptation of optical disk drive components to construct metrology tools such as a scanning optical microscope [2], an absolute position sensor [3], and an accelerometer [4, 5]. Within recent years, there has been increasing interest in the application of optical disk drives for biological sensing [6, 7, 8, 9, 10] and chemical analysis [11, 12, 13, 14]. Gordon [11] first demonstrated chemical analysis using optical disk drives, in which an additional photodiode was installed on an optical disk drive to perform transmission measurements through semi-transparent disks. In a similar approach, Morais et al. [6] used a modified optical disk drive to detect DNA hybridization on a CD surface. Alexandre et al. [7] realized an optical reader constructed from a modified optical disk drive that could process assays on both sides of a CD. Lange et al. [8] converted an optical disk drive into a scanning laser microscope, which was then used to image gold-nanoparticle-stained immunoassays. Recently, there have been efforts to develop methodologies for analysis and sensing using minimally-modified optical disk drive to preserve the simplicity of the disk drive operation and ease of use. Potyrailo et al. [12] developed a technique in which the analog signal was captured directly from the photodiode during the normal reading of a CD coated with colorimetric films, which enabled quantification of the concentration of metal ions in water. Further work demonstrated a Lab-on-Disk system for quantitative environmental sensing [13] and multi-wavelength operation using combo CD/DVD drives [14]. Another approach for using optical disk drives for analysis and sensing involves software implementations to analyze the digital signal obtained from a disk drive during normal reading of a CD. La Clair and Burkart [9] used the CD player manufacturer’s error determination in a standard CD/DVD drive for detection of streptavidin attached on a CD surface. A similar approach was reported by Li et al. [10], in which freely available CD-quality analysis software was employed to detect and to quantify biological binding events on the disc based on the rate of error detection.

In biological sensing and chemical analysis applications, a CD is modified by coating the bottom surface with analytes, and an optical disk drive quantifies the change in the optical properties of the CD due to the presence of the analytes. When the laser beam from the optical pickup system scans over regions of the CD containing analytes, the laser beam path is disrupted and the beam intensity measured by the photodiode is reduced. The reduction in the beam intensity can be measured by using software to determine the errors in the digital signal processed by the disk drive [9, 10] or by modifying the optical disk drive to measure the analog sum voltage signal directly from the photodiode prior to digitization [12, 13, 14]. The former approach does not require hardware modification to the drive. The latter approach is preferred, however, because
it enables quantitative measurement, has higher dynamic range, and can detect small changes in the sum voltage signal that are not sufficient to produce digitization errors.

An inherent limitation of sensing and imaging CD surfaces using optical disk drives is the presence of background voltage fluctuations acquired during the normal reading of the data on the CD. In this work, we propose a novel methodology to measure analytes on CDs using optical disk drives which mitigates the effect of the CD data. A sensor is realized by modifying an optical disk drive to capture the analog sum voltage signal from the photodiode integrated into the drive. The sensor is then used as an experimental platform to provide proof-of-concept demonstration of a simple, low-cost methodology for isolating the voltage signal contributions from the data on the CD and from the analyte on the CD surface. Analytes are first printed onto a CD surface in the form of patterns with high spatial periodicity. As the laser beam in the optical disk drive scans regions of the CD containing the analyte patterns, the intensity of the laser beam returning to the photodiode is modulated. Fourier transformation of the voltage signal from the photodiode yields characteristic peaks in the frequency spectrum with spectral locations corresponding to the modulation frequency of the laser beam due to the analyte pattern. The periodicity of the analyte pattern is tuned so that the peaks lie in a frequency range well below the peaks corresponding to the data on the CD. The dependence of the location and amplitude of the peaks is studied as a function of analyte area coverage, pattern periodicity, and optical disk drive motor speed. Using our sensor implementation and detection methodology, we demonstrate discrimination of differently-colored analytes, trigger-free detection of multiple analytes distributed about a CD, multiplexing of at least two different, overlapped analytes patterns, and radial-position feedback via analyte patterning. This work shows a new way to use CDs and optical disk drives for sensing which overcomes the noise associated with normal reading of the data on a CD. The methodology will have applicability in the development of next-generation, higher-sensitivity optical-disk-drive sensors.

2. Experimental Design

Figure 1(a) illustrates the basic components and operating principle of a CD and optical disk drive. The CD is composed of a thick protective polycarbonate layer and a metallic reflective layer. Data on a CD is encoded in a series of corrugations in a thin dye layer between the metallic and polycarbonate layers. These corrugations consist of thin and thick regions known as pit and land structures, respectively. During the reading of the CD, the optical disk drive motor rotates the CD and the pit-and-land structures on the CD are read by an integrated optical pickup system in the disk drive. The optical pickup system is composed of a laser diode emitting at a free-space wavelength $\lambda_0 = 780$ nm. The emitted laser beam is re-directed by a beam-splitter, collimated by a collimator lens, and then focussed by a movable objective onto the pit-and-land structures on the CD. The spot size of the focused beam on the pit-and-land structures is $\simeq 1.5 \mu$m. The beam reflected from the CD surface is focused by a cylindrical lens
onto a 4-quadrant photodiode. The analog voltage signal from each of the 4 quadrants of
the photodiode are added, which yields an analog sum voltage signal, \( V(t) \), proportional
to the intensity of the laser beam incident onto the photodiode. Depending on whether
the beam is focussed onto a pit or land structure on the CD surface, constructive or
destructive interference of the beam returning to the photodiode results in a voltage
signal that is relatively high or low, respectively. These modulations are visible in the
sum voltage signal captured during normal reading of a CD shown in Fig. 1(b). The
time-dependent modulations in the sum voltage signal are converted into a binary signal
by an integrated analog-to-digital converter.

This work is an experimental investigation to validate a new measurement
methodology. A modified optical disk drive is used to detect the presence of analytes
intentionally patterned to yield characteristic peaks in the frequency spectrum of the
voltage signal output from the drive. Key control variables of this study include the type
of CD, the type of optical disk drive, the pit-and-land structure on the CD, the radial
position of the optical pickup system, the speed of the motor spindle, and the type of
analyte on the CD surface. We use standard recordable CDs (Verbatim CD-R) that are
1.2 mm in thickness and 120 mm in diameter. One CD disk drive is used throughout the
experiments (Creative BCD 48SB). Burning data onto the CD is required for the drive
to read the CD. On each CD, a series of tracks are burnt composed of a single-frequency
audio signal (at either 100 Hz, 400 Hz, 800 Hz, or 1600 Hz). We vary the radial position
of the optical pickup system during normal reading of the CD by using a common
player software (Windows Media Player 11) to specify a track, where the first track
corresponds to the smallest radial position and the last track corresponds to the largest
radial position. We control the speed of the motor spindle during normal reading of the
CD by using a freely-available software (Nero DriveSpeed) compatible with nearly all
commercial disk drives. The analyte used in this study is colored ink, deposited onto
the CD surface either by application with a felt pen or using a commercially-available
ink-jet printer (Epson Artisan 50 CD/DVD/Photo Printer). The independent variable
of this study is the spatial periodicity of the analyte pattern on the CD surface. The
analyte pattern is generated using commercially-available drafting software (AutoCAD)
and printed onto the CD surface using an ink jet printer. The dependent variable
of this study is the power spectrum, \( P(f) \), of the sum voltage signal from the optical disk
drive. The sum voltage signal is measured by carefully soldering a wire onto the sum
output from the 4-quadrant photodiode and then connecting the wire to an oscilloscope
(Rigol DS1052E). With this minor hardware modification, \( V(t) \) can be measured during
reading of the CD without interfering with the normal feedback between the disk drive
and the computer. The sum voltage signal is recorded onto the oscilloscope and the
voltage signal spectrum, \( V(f) \), is obtained by Fourier transformation of \( V(t) \) using
standard analysis software (Matlab 7). The power spectrum of the voltage signal is
given by \( P(f) \propto |V(f)|^2 \).
3. Results and Discussion

3.1. Time-Domain Analysis

We demonstrate the detection of analytes on a CD based on the time-dependent change in \( V(t) \) as the optical pickup system of an optical disk drive scans the analyte-bearing CD (Fig. 2). The test analyte is colored ink, applied using a marker (Sharpie Fine Point Permanent Marker) in a \( \approx 2 \text{-mm-thick} \) line along the radial direction of the CD. The line is sufficiently thick to accommodate the entire laser beam spot size on the polycarbonate surface of the CD (\( \approx 700 \mu\text{m} \)). When the optical pickup system scans across the line on the CD, the laser beam is scattered and absorbed by the colored ink. This reduces the total beam intensity on the photodiode and obscures the pit and land structures on the CD causing, respectively, a decrease in the mean voltage signal and a reduction in the amplitude of the voltage fluctuations. The change in \( V(t) \) is dependent on the optical properties of the ink and the thickness of the ink layer on the CD surface.

One limitation of analyte detection based on time-domain observation of the changes in \( V(t) \) is the rapid background fluctuations. Depending on whether the laser beam is focused onto a pit or land structure on the CD, the amplitude of the voltage signal can vary by up to \( \pm 0.2 \text{V} \). If the analyte is semi-transparent at the laser wavelength or if the analyte occupies an area smaller than the laser beam spot size at the polycarbonate surface, it becomes increasingly difficult to distinguish the component of \( V(t) \) due to the analyte on the CD and that due to the pit and land structure.

3.2. Frequency-Domain Analysis

We next study the spectral characteristics of the voltage signal fluctuations created when the optical pickup system scans over the pit and land structures of a CD. Different CDs are prepared, with pit and land structures defined in the dye layer by burning tracks onto the CDs composed of single-frequency audio signals (100 Hz, 400 Hz, 800 Hz, and 1600 Hz). As shown in Figure 3, the voltage signal during reading of all the CDs contains a large, low-frequency component below \( \approx 3 \text{kHz} \) and several large-amplitude peaks located above \( \approx 50 \text{kHz} \). A “low-noise range” can be identified approximately between 3 kHz and 50 kHz over which the voltage signal fluctuations due to the pit and land structure contains minimal large-amplitude peaks.

When using optical disk drives for analyte sensing on a CD, discrimination of the voltage signal component due to the analyte and that due to the pit and land structure on the CD can be achieved by modulating the voltage signal component due to the analyte to produce a spectral peak in the aforementioned “low-noise” frequency range. We demonstrate this principle by depositing a analyte on a CD as a series of lines oriented along the radial direction and spaced with a fixed angular period along the azimuthal direction. The line density of the pattern is specified by the number of lines per full rotation, \( p \). At any radial position, the optical pickup system scans across the CD at a rotational frequency, \( f_{\text{rot}} \). As the optical pickup system scans across the
patterned analyte, the voltage signal is modulated at a frequency, $f_m$, given by

$$f_m = pf_{rot}.$$  \(1\)

The rotational frequency of the CD and the line density of the lines can be tuned to yield a modulation frequency between 3 kHz and 50 kHz. For CD rotational frequencies on the order of 10s of Hz, patterns with line densities of several hundred lines/rotation are required. These line densities are well within the resolution capabilities of standard, commercially-available ink jet printers. To experimentally test this methodology for analyte sensing, we perform proof-of-concept studies where a standard analyte, colored ink, is printed onto a CD using an ink jet printer according to a pattern generated using software. Figure 4(a) shows an optical micrograph of a analyte pattern with $p = 375$ lines/rotation, where the individual lines have a width of $w \simeq 0.5$ mm. The optical disk motor drive rotates at $f_{rot} = 26.6$ Hz. A thick black line is drawn on the CD to provide a triggering signal that is used to synchronize the timing of the oscilloscope with the azimuthal position of the optical pickup system. The drop in the voltage signal when the disk drives scans over the triggering line provides a reference time and azimuthal position where the oscilloscope begins recording the voltage signal from the optical disk drive. This triggering line is convenient because it allows the oscilloscope to capture only the data corresponding to the part of the CD surface containing the analyte pattern. It should be noted that the triggering line is not essential to the detection scheme. So long as the oscilloscope records the voltage signal as the optical disk drive scans at least one full revolution of the CD, the patterned analyte will be scanned by the optical pickup system and the triggering line is not needed. As seen in Fig. 4(b), the presence of the lines on the CD causes periodic spikes in $V(t)$. The ratio of the amplitude of the spikes corresponding to the lines on the CD and the amplitude of the fluctuations due to the pit and land structure of the CD is approximately $2 - 3$. As seen in Fig. 4(c), the visibility of the voltage signal component due to the patterned lines is enhanced in the frequency domain. The power spectrum shows pronounced frequency peaks at $10.1 \pm 0.1$ kHz and $20.1 \pm 0.1$ kHz nearly matching, respectively, the fundamental modulation frequency due to the lines calculated according to Eqn. 1 ($375$ rotations/rotation × $26.6$ rotations/s = 9975 Hz) and the second-harmonic of the modulation frequency. The amplitude of the fundamental peak is about three orders of magnitude greater than the amplitude at frequencies neighboring the peak.

3.3. Influence of the Angular Coverage of the Analyte Pattern

We next study the influence of angular coverage of the analyte pattern on the corresponding peaks in $P(f)$. Different analyte patterns are printed onto one of six CDs which have all been burnt with identical single-frequency 800 Hz audio tracks. The analyte patterns are printed with black ink, with fixed line density $p = 375$ lines/rotation, but with angular coverage that varies from $5^\circ$ to $35^\circ$. The optical disk motor drive rotates at $f_{rot} = 17.8$ Hz. As shown from the frequency spectrum spanning from 0 to 15 kHz [Fig. 5(a)], reducing the angular coverage of the analyte pattern causes
amplitude reduction, widening, and frequency-downshifting of both the fundamental and 
second-harmonic frequency peaks associated with the analyte pattern. The frequency 
spectra shown in Fig. 5 are calculated using a voltage signal of fixed total duration, 
encircling the duration when the optical pickup system scans across the analyte 
pattern. The amplitude reduction and widening of the peaks are attributed to the 
diminishing modulated portion of the voltage signal as the area coverage decreases. The 
frequency down-shifting is attributed to the low duty-cycle of the pattern (10 – 30%), 
which tends to lower the modulation frequency as the duration of the modulated signal 
decreases. For analyte patterning of visibly-opaque analytes, our measurements indicate 
that an angular coverage exceeding 5 ° is needed to maintain high visibility of the peaks in 
P(f) relative to the noise level. It is noteworthy that variation of the angular coverage 
of the analyte pattern does not significantly influence the general distribution of the 
low-frequency noise below 3 kHz.

3.4. Influence of the Line Density of the Analyte Pattern

For a fixed optical disk drive motor speed, variation of the line density of the analyte 
pattern shifts the spectral location of the peaks in P(f). We demonstrate this principle 
by printing different analyte patterns onto five CDs which have all been burnt with 
identical 800 Hz audio tracks. The analyte patterns are all printed with black ink, with 
fixed angular coverage of ≃ 30 °, but with line density that varies from 370 lines/rotation 
to 390 lines/rotation. The rotational frequency of the optical disk drive motor is fixed 
at f_{rot} = 17.8 Hz. As shown from the frequency spectrum spanning from 0 to 15 kHz 
[Fig. 6(a)], increasing the line density of the pattern from 370 lines/rotation to 390 
lines/rotation increases the position of the fundamental peak from 6.6 ± 0.1 kHz to 
7.0 ± 0.1 kHz and the second harmonic peak from 13.2 ± 0.1 kHz to 13.9 ± 0.1 kHz. The 
amplitude of the fundamental peak decreases approximately linearly with increasing line 
density. At the radial position of the optical pickup system (≃ 40 mm), the separation 
between the lines is ≃ 0.7 mm, which is on the order of the beam spot size at the 
polycarbonate surface of the CD (≃ 700 µm). As the line density increases, the optical 
pickup system scans more than one line at a time, which reduces the voltage modulation 
caused by each individual line during the scan and yields a reduction in the amplitude 
of the fundamental peak.

3.5. Influence of the Motor Drive Speed

The spectral location of the peaks corresponding to the analyte pattern can be shifted 
by variation of the optical disk motor speed. We print a analyte pattern onto a CD 
with a line density p = 375 lines/rotation. The pattern is scanned with the optical 
disk motor set at nominal motor drive speeds of 1×, 4×, and 8×, corresponding to CD 
rotational velocities of 4.6 Hz, 17.8 Hz, and 34.7 Hz, respectively. As shown in Fig. 7, 
increasing the motor speed shifts the fundamental and second-harmonic peaks to higher 
frequencies and reduces the amplitude of the peaks. The spectral position of the peaks
are linearly proportional to the CD rotational frequency, as expected from Eqn. 1.

### 3.6. Discrimination of Differently-Colored Analyte Patterns

We next demonstrate discrimination of differently-colored analytes by measuring their relative optical properties at the operating wavelength of the optical disk sensor, \( \lambda_0 = 780 \) nm. The optical properties of differently-colored analytes are quantified by scanning over analyte patterns of identical angular coverage and line density, composed of either black, red, blue, green, and yellow ink. The patterns are each printed onto a CD which has been burnt with identical, single-frequency 800 Hz audio tracks. The optical properties of the differently-colored patterns are quantified by the relative amplitudes of the fundamental peak in the frequency spectrum. Figure 8(a) shows the frequency spectrum spanning from 0 to 15 kHz for comparative voltage signals obtained by scanning the black and green ink patterns. For both the black and green analyte patterns, the fundamental peaks in the frequency spectrum are located at 10 kHz, matching the expected frequency peak given a line density \( \bar{p} = 375 \) lines/rotation and motor drive speed \( f_{\text{rot}} = 26.6 \) Hz. The color of the analyte can be distinguished based on the amplitude of the fundamental peaks. Fig. 8(b) summarizes the fundamental peak amplitudes obtained for the five differently-colored analyte patterns. The peak amplitude values for each color correspond to the mean of several measurements obtained along different radial positions, and the error bars correspond to one standard deviation in the measurements. Out of the five colors, only green and yellow can be uniquely identified. Red, blue, and black are indistinguishable, within the error of the measurement. It should be noted that color discrimination can be achieved by performing measurements at more than one wavelength. This could potentially be achieved by a sensor based on a CD/DVD/Blu-ray combination optical disk drive operating at up to three discrete wavelengths in the visible range.

### 3.7. Parallel Measurements of Analyte Patterns

Parallel measurements can be performed by printing multiple analyte patterns, each with different line densities, onto a single CD. When at least one full rotation of the CD is read by the optical disk drive, the patterns can be identified by characteristic peaks in the frequency spectrum of the voltage signal. This is demonstrated by printing five different patterns onto different sections of a single CD with pit-and-land structures defined by burning audio tracks composed of a 800 Hz audio signal. The five analyte patterns have line densities ranging from 210 lines/rotation to 370 lines/rotation. The patterns are composed of black ink with a fixed angular coverage of \( \simeq 30^\circ \), and the speed of the optical disk drive motor is fixed at \( f_{\text{rot}} = 17.8 \) Hz. No triggering lines are drawn onto the CD because the voltage signal is collected over more than one full rotation of the CD. As shown from the frequency spectrum spanning from 0 to 8 kHz (Fig. 9), the voltage signal contains five distinctive peaks located at 3.7 kHz, 4.4 kHz, 5.2 kHz, 5.8 kHz, and 6.5 kHz. The location of the peaks match the modulation frequencies of the voltage
signal given the fixed motor speed and the respective line densities of the patterns. Multiple analytes on a CD can thus be uniquely identified by their respective peaks, enabling parallel optical characterization of analytes based on the peak amplitudes.

3.8. Multiplex Measurements of Analyte Patterns

Frequency-domain analysis of the voltage signal permits multiplex measurements in which multiple analyte patterns printed over top of each other are sensed and identified by performing a single measurement. To demonstrate this capability, multiple analyte patterns with different line densities are printed over top of each other on the same region of a CD surface. By recording the voltage signal as the optical pickup head scans over this region of the CD, the multiple, overlapped patterns can be identified from their respective peaks in the Fourier spectrum of the voltage signal obtained by scanning over this region of the CD surface. We demonstrate multiplexing by printing two analyte patterns with line densities of 250 lines/rotation and 330 lines/rotation over the same area of a CD. The patterns are composed of black ink, with a fixed angular coverage of $\simeq 30^\circ$. The speed of the optical disk drive motor is fixed at $f_{\text{rot}} = 17.8$ Hz. As shown in Fig. 10, $P(f)$ obtained by scanning over the region of the CD containing the overlapped patterns contains two distinctive peaks located at $4.3 \pm 0.2$ kHz and $5.8 \pm 0.2$ kHz, matching the modulation frequency corresponding to the two patterns ($250/\text{rotation} \times 17.8 \text{ rotations/s} = 4450 \text{ Hz}$ and $330/\text{rotation} \times 17.8 \text{ rotations/s} = 5874 \text{ Hz}$).

3.9. Position Feedback using Analyte Patterns with Radially-Dependent Line Densities

Thus far, we have used analyte patterns composed of lines oriented along the radial direction with a fixed line density, where the radial position of the optical pickup system is specified by selecting a particular track on the CD using media software. Dynamic feedback on the radial position of the optical pickup system can be obtained by patterning the analyte with a known, radially-dependent line density and then calculating the radial position of the optical pickup system based on the frequency position of the peak. We print a pattern on a CD in which the line density varies from 140 lines/rotation to 400 lines/rotation over the radius of the CD, as shown in Fig. 11(a). The speed of the optical disk drive motor is fixed at $f_{\text{rot}} = 17.8$ Hz. Figure 11(b) shows the power spectrum spanning from 0 to 8 kHz when the optical pickup system scans the pattern at three different radial positions $a$, $b$, and $c$. The power spectra corresponding to the three scans each contain a distinctive peak located at $3.5 \pm 0.3$ kHz, $4.2 \pm 0.3$ kHz, and $4.9 \pm 0.3$ kHz, respectively. Based on the spectral position of the fundamental peak and the radial dependence of the line density, the radial positions of the optical pickup system for the three scans are $a = 41 \pm 1$ mm, $b = 46 \pm 1$ mm, and $c = 50 \pm 1$ mm.
3.10. Potential Application for Reagent Sensing and Identification

Thus far, we have demonstrated that colored analytes intentionally patterned onto a CD surface can be detected and identified by frequency-domain analysis of the voltage signal from the optical disk drive as it scans the CD. In this section, we will discuss the potential applicability of this measurement principle to perform massively-parallel assays based on reagents (substances that undergo a chemical reaction to produce a measurable byproduct) patterned onto a CD surface. Reagents compatible with this methodology include colorimetric reagents that visibly change color in the presence of a target species and thus, causes the reflectivity of the CD surface to change at the operating frequency of the optical disk drive. As examples, possible colorimetric reagents compatible with CD optical disk drives include Bromophenol blue, which changes from deep purple to yellow as the pH drops from above 4.6 to below 3.0, or Xylidyl blue [12], which changes from clear to reddish violet in the presence of Mg. Once suitable reagents are chosen, multiple reagents can be printed onto the CD surface in patterns having different line densities. Many patterns can be printed onto one CD by exploiting the methods that we have discussed above, such as printing multiple reagent patterns with different line densities on top of each other. An assay is performed by scanning the reagent-bearing CD with an optical disk drive twice, once before exposure to establish reference levels and again after exposure. From the voltage signal spectrum, the individual reagent patterns can be identified by their characteristic spectral peaks (located at frequencies correlated to the line densities of the patterns), and the change in the optical properties of the reagents can be quantified in a highly parallel fashion by the change in the amplitude of their spectral peaks after exposure.

3.11. Limitations

We note several limitations with our sensor implementation. One limitation is the lack of control over the feedback of the optical disk drive. Our sensor is implemented by simply capturing the analog voltage signal from the optical disk drive during normal operation of the drive. When the optical disk drive scans over the analyte pattern, errors are generated in the digital signal from the disk drive. When the analyte pattern encompasses a large angular coverage or when the line density is too high, significant errors accumulate in the digital signal, and the disk drive stops functioning altogether. We have noticed disk drive stoppage, for example, when the disk drive scans a analyte pattern of 375 lines/rotation and 40% angular coverage or a continuous, opaque analyte with more than 5% angular coverage. The threshold error before the drive stops functioning generally varies between different drives. Another limitation is the hydrophobicity of the polycarbonate surface of the CD, which limits the adhesion of water-based analytes to the CD. When the CD spins, centrifugal force pushes the water-based analytes along the radial direction, causing a smearing of the pattern towards the outer edge of the CD surface. Rotation of the CD at very high frequencies can completely remove the analyte from the CD surface.
4. Conclusions

Sensing of substances on a CD based on the time-dependent signal from an optical disk drive is limited by the fluctuations in the voltage signal generated during normal reading of the data on a CD. We have demonstrated a simple, low-cost technique for analyte sensing and identification using optical disk drives that separates contributions to the voltage signal caused by the analyte and that caused by the data on the CD. Analytes are first applied to a CD in the form of patterns with high spatial periodicity. When the analyte-bearing CD is read by an optical disk drive, the voltage signal from the photodiode integrated into the drive is modulated at a frequency dependent on the analyte pattern periodicity and the disk drive motor speed. Fourier transformation of the voltage signal yields peaks in the frequency spectrum associated with the analyte pattern. By judiciously selecting the pattern periodicity and the motor drive speed, the peaks can be positioned in a spectral region where the signal due to the data on the CD is minimal. The merits of this approach include high analyte-signal visibility, the ability to identify analytes based on characteristic spectral peaks, and the possibility of performing parallel multiplex measurements of multiple analytes patterns of different period over a fixed region of the CD. Future directions of this work include the adaptation of this methodology to combo CD/DVD/Blu-ray drives to perform multi-wavelength measurements and the development of software approaches to overcome the accumulation of significant error in the digital signal from the drive.

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6. References


Figure 1. (a) Schematic of the optical pick-up system. (b) Typical analog sum photodiode signal captured from the photodiode of the optical disk drive during the scanning of a CD.
Figure 2. Discrimination of analytes based on the time-domain voltage signal from an optical disk drive. Time-domain voltage signal as the optical disk drive scans across the ≃ 2 mm-thick black ink line (top) and ≃ 2 mm-thick green ink line (bottom) drawn on the CDs. The voltage signal is composed of high-frequency oscillations due to constructive and destructive interference of the laser beam. The mean signal level and the amplitude of the high-frequency oscillations momentarily decrease as the disk drive scans across the line. The yellow curves correspond to the averaged signal in the absence of the high-frequency oscillations.
Figure 3. Fourier transform of the voltage signal as the optical disk drive reads CDs containing audio signals at 100 Hz, 400 Hz, 800 Hz, and 1600 Hz.
Figure 4. (a) Optical micrograph of a analyte pattern printed onto a CD composed of black ink with a line density $p = 375$ lines/rotation. (b) Time-domain voltage signal and (c) the power spectrum as the optical disk drive scans the patterned analyte. Scanning over the patterned analyte yields a first harmonic peak and a second harmonic peak in the power spectrum located at 10 kHz and 20 kHz, respectively.
Figure 5. Influence of the pattern coverage on the power spectrum of the voltage signal from the optical disk drive. (a) Power spectrum of the voltage signal obtained by scanning the optical disk drive at a speed of 17.8 Hz over analyte patterns composed of fixed line density 375 lines/rotation as the angular coverage varies from 35° to 5°. (b) plots a magnified view of the first harmonic peak in the frequency spectrum. Images of the analyte patterns are shown on the right.
Figure 6. Influence of line density on the frequency spectrum of the voltage signal from the optical disk drive. (a) Power spectrum of the voltage signal obtained by scanning the optical disk drive over analyte patterns composed of fixed angular coverage $\simeq 30^\circ$ as the line density varies from 370 lines/revolution to 390 lines/revolution. (b) plots a magnified view of the first harmonic peak. Images of the analyte patterns with line densities of 370 lines/revolution to 390 lines/revolution are shown above.
Figure 7. Power spectrum of the voltage signal obtained by scanning the optical disk drive over analyte patterns composed of fixed angular coverage ≃ 30° and fixed line density 375 lines/rotation as the motor speed is varied from 1× to 8×.
Figure 8. Color discrimination of black and green analyte patterns using an optical-disk-drive sensor operating in the frequency domain. (a) Power spectrum of the voltage signal obtained by scanning the optical disk drive over analyte patterns composed of black and green ink with a line density of 375 lines/rotation at fixed disk rotation speed of 17.8 Hz. Color is discriminated by the amplitude of the first harmonic peak located at 10 kHz. (b) Average amplitude of the peak when the analyte pattern is composed of black, red, blue, green, and yellow ink. The error bars correspond to the standard deviation obtained from sets of at least 5 runs.
Figure 9. Power spectrum of the voltage signal obtained by scanning the optical disk drive over a CD containing 5 analyte patterns with line densities of 210, 250, 290, 330, and 370 lines/rotation at a disk rotation speed of 17.8 Hz at three different radial positions. The inset shows an optical micrograph of the CD with the printed analyte patterns.
Figure 10. Power spectrum of the voltage signal obtained by scanning the optical disk drive over a region of a CD containing 2 overlapping analyte patterns with angular periods of 270 lines/rotation and 330 lines/rotation at a disk rotation speed of 17.8 Hz. The inset shows an optical micrograph of the CD with the printed analyte patterns.
Figure 11. (a) Line density as a function of the radial position of a printed pattern. (b) Power spectrum of the voltage signal obtained by scanning the optical disk drive over the pattern at a disk rotation speed of 17.8 Hz for three different radial positions a, b, and c. The inset shows an optical micrograph of the CD with the printed analyte pattern.