



(51) International Patent Classification:

Not classified

Published:

— without international search report and to be republished upon receipt of that report (Rule 48.2(g))

(21) International Application Number:

PCT/US2017/022527

(22) International Filing Date:

15 March 2017 (15.03.2017)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/308,347 15 March 2016 (15.03.2016) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

(54) Title: SUBSTRATE DEFECT BASED DEMODULATION

(57) Abstract: Devices and methods for demodulating a frequency modulated electromagnetic wave are provided. In various embodiments, a device includes a substrate comprising at least a first region having a plurality of atomic defects therewithin. The device includes a light source configured to emit electromagnetic radiation of a first wavelength and to illuminate the first region of the substrate. The first region of the substrate emits electromagnetic radiation of a second wavelength when exposed to electromagnetic radiation of the first wavelength. The device includes a photodetector configured to detect electromagnetic radiation of the second wavelength. The photodetector is configured to detect electromagnetic radiation emitted by the first region of the substrate.



SUBSTRATE DEFECT BASED DEMODULATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/308,347, filed on March 15, 2016, the entirety of which is hereby incorporated by reference.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0002] This invention was made with Government support under Grant No. FA9550-12-1-0025 awarded by the U.S. Air Force Office of Scientific Research and Grant No. HR0011-111-C-0073 awarded by the Defense Advanced Research Projects Agency (DARPA). The Government has certain rights to this invention.

BACKGROUND

[0003] Embodiments of the present disclosure relate to nanoscale devices for demodulating an input electromagnetic wave, and more specifically, to substrate defect based demodulation.

BRIEF SUMMARY

[0004] According to embodiments of the present disclosure, a device for demodulating a frequency modulated electromagnetic wave is provided. The device includes a substrate comprising at least a first region having a plurality of atomic defects therein. The device includes a light source configured to emit electromagnetic radiation of a first wavelength and to illuminate the first region of the substrate. The first region of the substrate emits electromagnetic radiation of a second wavelength when exposed to electromagnetic radiation of the first wavelength. The device includes a photodetector configured to detect electromagnetic radiation of the second wavelength. The photodetector is configured to detect electromagnetic radiation emitted by the first region of the substrate.

B4658675.2

[0005] In some embodiments, the first region of the substrate is adapted to be exposed to a frequency-modulated electromagnetic input having a wavelength range. In some embodiments, the intensity of the electromagnetic radiation emitted by the first region of the substrate, when illuminated by the light source, varies substantially linearly with the frequency of the frequency-modulated electromagnetic input. In some embodiments, the first region of the substrate is tuned to the wavelength range of the frequency-modulated electromagnetic input. In some embodiments, the wavelength range of the frequency-modulated electromagnetic input is from about 300 MHz to about 300 GHz.

[0006] In some embodiments, the device includes a magnetic field source configured to expose the first region of the substrate to a magnetic field and thereby to tune the first region of the substrate to the wavelength range of the frequency-modulated electromagnetic input. In some embodiments, the magnetic field source is tunable.

[0007] In some embodiments, the substrate comprises a crystalline solid. In some embodiments, the substrate comprises diamond. In some embodiments, the substrate comprises crystalline silicon. In some embodiments, the plurality of atomic defects comprises nitrogen-vacancy centers. In some embodiments, the plurality of atomic defects comprises silicon vacancy centers. In some embodiments, the light source comprises a laser. In some embodiments, the first wavelength is about 532 nm. In some embodiments, the first region of the substrate has a characteristic size of about 200 μm . In some embodiments, the second wavelength is about 632 nm.

[0008] In some embodiments, the first region has a surface area of about 100 μm^2 . In some embodiments, the plurality of atomic defects has a density of about 10^{17} cm^{-3} to about $2 \times 10^{17} \text{ cm}^{-3}$ within the substrate. In some embodiments, the light source is configured to illuminate about 10^7 atomic defects.

[0009] According to other embodiments of the present disclosure, a method for detecting a frequency modulated electromagnetic wave is provided. A device is exposed to a frequency-modulated electromagnetic input having a wavelength range. The device includes a substrate, comprising at least a first region having a plurality of atomic defects therewithin, a light source configured to emit electromagnetic radiation of a first wavelength and to illuminate the first region of the substrate, said first region emitting electromagnetic radiation of a second wavelength when exposed to electromagnetic radiation of the first wavelength, and a photodetector configured to detect electromagnetic radiation of the second wavelength, said photodetector configured to detect electromagnetic radiation emitted by the first region of the substrate. Electromagnetic radiation of the first wavelength emitted by the light source is directed to the first region of the substrate, thereby causing the first region of the substrate to emit electromagnetic radiation of the second wavelength. Electromagnetic radiation emitted by the first region of the substrate is detected by the photodetector.

[0010] In some embodiments, the intensity of the electromagnetic radiation emitted by the first region of the substrate, when illuminated by the light source, varies substantially linearly with the frequency of the FM input.

[0011] In some embodiments, the first region of the substrate is exposed to a magnetic field, thereby tuning the first region of the substrate to the wavelength range of the frequency-modulated electromagnetic input. In some embodiments, the wavelength range of the frequency-modulated electromagnetic input is from about 300 MHz to about 300 GHz.

[0012] In some embodiments, the substrate comprises a crystalline solid. In some embodiments, the substrate comprises diamond. In some embodiments, the substrate comprises crystalline silicon. In some embodiments, the plurality of atomic defects comprises nitrogen-vacancy centers. In some embodiments, the plurality of atomic defects comprises silicon vacancy centers. In some embodiments, the light source comprises a laser.

In some embodiments, the first wavelength is about 532 nm. In some embodiments, the first region has a characteristic size of about 200 μm . In some embodiments, the second wavelength is about 632 nm.

[0013] In some embodiments, the first region has a surface area of about 100 μm^2 . In some embodiments, the plurality of atomic defects has a density of about 10^{17} cm^{-3} to about $2 \times 10^{17} \text{ cm}^{-3}$ within the substrate. In some embodiments, the light source is configured to illuminate about 10^7 atomic defects.

[0014] According to other embodiments of the present disclosure, an apparatus for demodulating an input electromagnetic wave is provided. The apparatus includes: a substrate including atomic defects; a magnetic field source; an optical wave source; and an electromagnetic wave detector; wherein an intensity of a magnetic field provided by the magnetic field source is configured to provide a detuning of a resonance in an interaction between the input electromagnetic wave and fluorescence excited by an optical wave provided by the optical wave source, such that an intensity of an output fluorescence signal detected by the electromagnetic wave detector is approximately linearly dependent on a frequency of the input electromagnetic wave.

[0015] In some embodiments, the substrate comprises a crystalline solid. In some embodiments, the atomic defects comprise point defects. In some embodiments, the point defects comprise vacancy defects. In some embodiments, the substrate comprises diamond and the vacancy defects comprise Nitrogen vacancy centers. In some embodiments, the optical wave source comprises a laser. In some embodiments, the magnetic field source is configured to provide a static magnetic field with an intensity that is tunable over a range.

[0016] According to other embodiments of the present disclosure, an apparatus includes: a magnetic field source; an optical wave source; and a demodulator configured to receive a static magnetic field from the magnetic field source and an optical wave from the optical

wave source within a diamond substrate that includes Nitrogen-vacancy centers, and to demodulate a frequency modulated input electromagnetic wave to provide an intensity variation on an output fluorescence signal.

[0017] According to other embodiments of the present disclosure, an apparatus for demodulating an input electromagnetic wave includes: optical wave source; and a demodulator configured to provide an output optical signal in response to the input electromagnetic wave interacting within a substrate that receives an optical wave from the optical wave source and responds to the optical wave by exciting states of atomic defects within the substrate to at least two excited states that include a first excited state and a second excited state, wherein the first excited state includes a non-radiative pathway that is not as strong for the second excited state as for the first excited state, and an intensity of the output optical signal is approximately linearly dependent on a frequency of the input electromagnetic wave.

[0018] According to other embodiments of the present disclosure, a method for demodulating an input electromagnetic wave includes: applying a magnetic field to a first portion of a substrate; applying an optical wave to the first portion of the substrate; receiving the input electromagnetic wave into the first portion of the substrate; and detecting an intensity of an output fluorescence signal from the substrate, wherein atomic defects in the first portion of the substrate provide an interaction between the input electromagnetic wave and fluorescence excited by the optical wave, such that frequency modulation of the input electromagnetic wave is converted to intensity variation of the output fluorescence signal.

[0019] In some embodiments, applying the magnetic field includes selecting an intensity of the magnetic field to provide a detuning of a resonance in the interaction, such that the detected intensity of the output fluorescence signal is approximately linearly dependent on a frequency of the input electromagnetic wave.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0020] Fig. 1 is a schematic diagram of a demodulation device according to embodiments of the present disclosure.

[0021] Fig. 2 is a schematic diagram of a demodulation device according to embodiments of the present disclosure.

[0022] Fig. 3 is a schematic diagram illustrating the electronic energy levels of a negatively-charged NV center according to embodiments of the present disclosure.

[0023] Fig. 4 is a graph of microwave (MW) detuning (in MHz) relative to fluorescence intensity (in arbitrary units) illustrating the electron spin resonance spectrum of NVs in diamond according to embodiments of the present disclosure.

[0024] Fig. 5 is a graph of an original signal and a signal received through a device according to the present disclosure.

[0025] Fig. 6 is a graph of an original signal and a signal received through a device according to the present disclosure.

[0026] Fig. 7 is a graph of an original signal and a signal received through a device according to the present disclosure.

[0027] Fig. 8 is a graph of relative response (dB) relative to signal frequency (kHz), illustrating the relative response of the received signal based on the frequency of the original signal according to embodiments of the present disclosure.

[0028] Fig. 9 is a histogram of the harmonic distortion of the received signal according to embodiments of the present disclosure.

[0029] Fig. 10 is a schematic diagram of a nitrogen-vacancy (NV) radio receiver according to embodiments of the present disclosure.

[0030] Fig. 11 is a graph of microwave (MW) detuning (in MHz) relative to fluorescence intensity (in arbitrary units) illustrating the principle of NV FM microwave demodulation.

[0031] Fig. 12 is a graph of input and output waveforms, illustrating the input FM microwave signal to be demodulated and resulting output amplitude-modulated fluorescence signal according to embodiments of the present disclosure.

[0032] Fig. 13 is a graph of an original signal and a signal received through a device according to the present disclosure.

[0033] Fig. 14 is a graph of an original signal and a signal received through a device according to the present disclosure.

[0034] Fig. 15 is a graph of an original signal and a signal received through a device according to the present disclosure.

[0035] Fig. 16 is a graph of optical response (dB) relative to modulating frequency (Hz), illustrating the optical response of an NV radio receiver on the frequency of modulating signals according to embodiments of the present disclosure.

[0036] Fig. 17 is a histogram of the harmonic distortion of the output fluorescence intensity according to embodiments of the present disclosure.

[0037] Fig. 18 is a graph of optical response (arbitrary units) relative to electromagnetic voltage (V), illustrating optical response on the dc magnetic field B_0 under different environmental temperatures according to embodiments of the present disclosure.

[0038] Fig. 19 is a graph of response amplitude (arbitrary units) relative to temperature ($^{\circ}\text{C}$), illustrating the maximum responses on the environmental temperature according to embodiments of the present disclosure.

[0039] Fig. 20 is a graph of electromagnetic voltage (V) relative to temperature ($^{\circ}\text{C}$), illustrating the optimum electromagnetic voltages required to compensate for the temperature shifts according to embodiments of the present disclosure.

DETAILED DESCRIPTION

[0040] In their simplest form, a radio transmitter imprints the signal to be transmitted onto the amplitude, frequency, or phase of a carrier signal, while a receiver demodulates the radio waves to retrieve the information. Detection of frequency-modulated (FM) microwave signals is needed for low-noise FM spectroscopy and wireless communications.

[0041] Various techniques may be used to demodulate a frequency-modulated signal to recover a corresponding amplitude varying signal. For example, various demodulators use an integrated circuit with analog and/or digital circuitry to perform such demodulation. However, many modern applications require small and robust receivers that can operate in high temperature (*e.g.*, greater than 100 °C), high pressure, and/or chemically harsh environments. Integrated circuitry is not suitable for operation in such extreme environments (for example, being limited to operation below 85 °C). Accordingly, there is a need in the art for durable and miniaturized demodulators that can withstand extreme environments.

[0042] In various embodiments of the present disclosure, diamond-based detectors are provided. Such diamond devices can operate in extremely challenging conditions, including high pressure over 60 GPa, high temperature over 600 K (326.85°C), and corrosive environments. Moreover, diamond-based detectors are suitable for *in vivo* use, due to the biocompatibility of diamond.

[0043] According to various embodiments, electrons in diamond nitrogen-vacancy (NV) centers (or “color center”) are powered, or pumped, by green light emitted from a laser. These electrons are sensitive to electromagnetic fields, including the waves used in FM radio, for example. When an NV center receives radio waves, it emits a signal as red light. A photodiode converts that light into a current, which is then converted to sound through a speaker or headphone. An electromagnet creates a strong magnetic field around the

diamond, which can be used to tune the receiving frequency of the NV centers (which is analogous to changing a radio station on a conventional radio).

[0044] More particularly, the present disclosure provides for diamond NV-based radio receivers that are capable of transducing frequency modulated (FM) microwave radio signals to amplitude modulated (AM) optical fluorescence signal (intensity-modulated fluorescence). Devices according to the present disclosure take advantage of the fact that the photoluminescence of an NV center depends on its electron spin state, which is sensitive to microwave radiation. Transmission of high-fidelity audio is demonstrated and the bandwidth of the diamond radio receiver is measured to be about 91 kHz. The operating temperature of a diamond radio can be at least as high as 350 °C. In an exemplary embodiment, a FM radio receiver is provided with carrier frequency in S band and signal cutoff frequency of 56 kHz, which is adequate for high-quality audio radio.

[0045] Referring now to Fig. 1, an example of a demodulation device 100 is shown. The device 100 includes a substrate 102 including atomic defects 104 (*e.g.*, vacancy defects), a magnetic field source 106 providing a magnetic field 108 (*e.g.*, a static magnetic field), an optical wave source 110 providing an optical wave 112 (*e.g.*, a laser beam), an electromagnetic wave detector 114 (*e.g.*, a photodiode detector, or other optical detector) for detecting an output optical signal 116 (*e.g.*, a fluorescence signal) from an input electromagnetic wave 118. In some embodiments, the input electromagnetic wave 118 is a microwave electromagnetic wave that is carried by a waveguide (not shown) on the substrate 102. The demodulation device 100 is configured and operated such that a frequency modulation on the input electromagnetic wave 118 is demodulated to an amplitude variation on the output optical signal 116.

[0046] As noted above, in various embodiments, substrate 102 comprises diamond and defects 104 are NV centers. Input wave 118 includes a frequency modulated signal. In

order to extract sufficient intensity data over time, the optical detector 114 must have sufficient temporal resolution, and there must be sufficient density of NV centers to provide detectable output at that temporal resolution of the detector. In particular, a single NV center is unsuitable for detection by a high temporal resolution detector because the signal to noise ratio (SNR) would be too high. Accordingly, a high speed optical detector with a wide field directed at a region dense with NV centers is suitable for use according to the present disclosure.

[0047] NV centers emit fluorescent light when optically excited, for example by optical input 112. The emitted light may be conceptualized as a stream of photons, and follows Poisson statistics. In experimental conditions, 1 million photons/sec are typically collected from single NV centers. Poisson statistics dictate that the noise is the square root of the count, which is 1000/sec. Given a target signal bandwidth of 1 MHz, 1 photon is counted at a MHz rate from a single NV. The noise scales with the square root of the bandwidth, resulting in an average noise of 1 photon counted per time interval. Therefore, the signal-to-noise ratio would be 1 (for reference, typical iPod audio has SNR ~ 100dB, 10 billion times better).

[0048] This relationship may be summarized as in Equation 1, where N is the photon counts per second and BW is the bandwidth of the detection. To achieve 100 dB SNR at $BW = 1$ MHz, using the above equation, $N = 10^{16}$, requiring 10 billion NV's to be excited simultaneously. The exemplary embodiments discussed below exhibit excitation of NV centers on this scale.

$$SNR (dB) = 20 \log \frac{N}{\sqrt{N BW}}$$

Equation 1

[0049] One can observe from the equation that there exist a tradeoff between SNR and BW for a given amount of collected photons N . Therefore, a high density of NV centers is

required for radio application, where high bandwidth and high SNR are needed. For example, to provide CD quality, the minimum SNR would be about 65,536, and minimum bandwidth would be about 44.1 kHz.

[0050] In various exemplary embodiments described below, the density of NV centers in diamond is about 10^{17} cm^{-3} to about $2 \times 10^{17} \text{ cm}^{-3}$. Given an illumination area of about $100 \mu\text{m}^2$, and an effective thickness of about $1 \mu\text{m}$, about 10^7 NV centers are active.

[0051] In radio applications, a non-linearity in response would result the distortion of the audio signal. Accordingly, linearity is desirable to support a high-quality audio signal. As shown further below, particularly with regard to **Fig. 9**, NV-based systems according to the present disclosure provide such a linearity.

[0052] With reference now to **Fig. 2**, a schematic diagram of a demodulation device according to embodiments of the present disclosure is provided, illustrating the microwave (MW) FM demodulation by NV centers. **Fig. 3** is a schematic diagram illustrating the electronic energy levels of a negatively-charged NV center. The ground state is a spin triplet with a splitting $\delta\omega + D_0$ between the spin-0 ground state $|0\rangle_g$ and the spin-1 ground state $|1\rangle_g$, determined by a crystal field splitting D_0 , and a Zeeman shift $\delta\omega$ induced by the bias magnetic field B_0 . The non-radiative pathway (wiggly arrows) enables optical polarization and readout of the NV spin states, where the $|0\rangle$ has a stronger fluorescence than the $|1\rangle$. **Fig. 4** is a graph of microwave (MW) detuning (in MHz) relative to fluorescence intensity (in arbitrary units) illustrating the electron spin resonance spectrum of NVs in diamond. The resonance of NVs is detuned at the maximum slope of the fluorescence intensity, and thus the frequency modulation of the MW is mapped to the NV fluorescence intensity.

[0053] An exemplary FM microwave demodulation device is depicted in **Fig. 2**, the FM microwave electromagnetic (EM) field **201** is delivered to a diamond plate **202** with dense NV centers via an on-chip microstrip **203**. A 532 nm probe laser **204** is focused on the

surface of the diamond, while red fluorescence 205 is collected by the same objective 206 and measured by a photodetector (PD) 207, generating a demodulated signal 208.

[0054] The negatively-charged NV center is a lattice defect in diamond, which consists of a substitutional nitrogen atom and an adjacent vacancy. According to the electronic energy levels of negatively-charged NV centers, as shown in Fig. 3, a resonant microwave EM field can drive NVs between two ground spin states, $|0\rangle_g$ and $|1\rangle_g$, and a 532 nm laser can excite the NVs to the excited state with spin conservation, and provide a spin-dependent fluorescence intensity due to the non-radiative pathway from the spin-1 excited state.

[0055] The non-radiative pathway provides a way for the radiative (fluorescence) energy generated from the spin-1 excited state to be weaker than the radiative (fluorescence) energy generated from the spin-0 excited state because some of the energy from the spin-1 excited state escapes into phonons that are absorbed by the diamond substrate (especially close to resonance with the input microwave EM field, which can be seen by the dip in the fluorescence intensity in Fig. 4). The spin-0 excited state does not have as strong of a nonradiative pathway for energy to escape as the spin-1 excited state. In other words, the fluorescence intensity of a NV is lowered when a resonant microwave EM field is present, as shown in Fig. 4.

[0056] The resonant frequency for microwaves is determined by a crystal field splitting $D_0 = 2.87$ GHz, as well as a Zeeman shift when a static (DC) bias magnetic field B_0 is present. With a bias magnetic field strength in the range of around 0 - 18 milliteslas (mT) (18×10^{-3} T), where the dependence between resonance frequency and magnetic field strength is around 28 MHz/mT, the resonant frequency can be tuned over a 500 MHz frequency range, which can be further extended using a stronger bias magnetic field (*e.g.*, a field strength of around 2 - 3 T would provide a larger operational tuning range). To achieve FM demodulation, the NV is slightly detuned from the microwave carrier frequency, as

illustrated in Fig. 4, where the horizontal axis is frequency detuning away from the resonant frequency determined by B_0 , the variation of the microwave frequency is then mapped to the intensity of the NV fluorescence.

[0057] Substrates other than diamond and/or substrates containing defects other than vacancy defects may also be used according to the operating principles provided herein. For example, in diamond, the vacancy defects could be Silicon vacancy centers. The substrate could be a semiconductor, such as Silicon. The defects could be naturally occurring, or artificially induced within the substrate.

[0058] Referring now to Figs. 5-7, graphs are provided of original signals and signals received through a device such as described above with reference to Fig. 2. The original signal is frequency-modulated on a carrier microwave by a microwave function generator. The FM microwave is then received and demodulated by NVs as outlined above, with the fluorescence intensity measured by a photodetector. Fig. 5 illustrates a 1 kHz sine wave. Fig. 6 illustrates a squared wave. Fig. 7 illustrates a music waveform. In each case, the original signal is displayed above the demodulated signal.

[0059] Fig. 8 is a graph of relative response (dB) relative to signal frequency (kHz), illustrating the relative response of the received signal based on the frequency of the original signal. Different carrier microwave powers (MW) and DC fluorescence intensities (Fl.) lead to various cutoff frequencies.

[0060] Fig. 9 is a histogram of the harmonic distortion of the received signal, when the original signal is a 1 kHz sine wave and the maximum frequency deviation from carrier frequency is 2.42 MHz. The total harmonic distortion (fundamental) is calculated as total higher harmonic frequency intensities divided by fundamental frequency intensity to be 2.67%.

[0061] In demonstrations of an exemplary device according to the present disclosure, the waveforms described above were received and demodulated by NV centers. The original signal is frequency-modulated on a carrier microwave of 2.857 GHz with maximum frequency deviation of 2.5 MHz from the carrier frequency, *i.e.*, the microwave frequency varies from 2.8545 to 2.8595 GHz. As shown in Figs. 5-7, a 1 kHz sine wave, a 1 kHz square wave, and a clip from a music waveform are demodulated to provide an amplitude (or intensity) varying signal (or baseband signal) that is consistent with the original signals sent to the microwave generator to be frequency modulated on the carrier microwave signal.

[0062] The frequency responses are measured under the various conditions of carrier microwave powers and probe laser intensities. While the 3 dB cutoff frequency is measured as 56 kHz with microwave power of -5 dBm at transmitter, the cutoff frequency is lowered to 41 kHz when the microwave power is attenuated to -15 dBm. Similarly, when the probe laser power is attenuated by a neutral-density filter (ND=1.0), the fluorescence intensity attenuates accordingly, and the cutoff frequency is lowered to 13.6 kHz.

[0063] Distortion is an important figure of merit that describes communication systems. An estimate of the harmonic distortion of the exemplary NV FM demodulator using a lock-in amplifier, is shown in Fig. 9. A total harmonic distortion of 2.67% is exhibited when the maximum frequency deviation of microwave is 2.42 MHz. The dynamic range of frequency deviation of the exemplary NV demodulator is about 4.8 MHz, which is consistent with the linewidth of the high-density-NV diamond sample used in this example.

[0064] Referring now to Fig. 10, a schematic view of a nitrogen-vacancy (NV) radio receiver is provided according to embodiments of the present disclosure. The NV centers 1001 in diamond 1002 demodulate frequency-modulated (FM) microwave signals 1003 and map it onto fluorescence 1004. The NV centers 1001 are pumped by a green (532 nm) laser

1005. The dc magnetic field B_0 1006 is applied to tune the detecting carrier frequency of the microwave signal 1003.

[0065] Fig. 11 is a graph of microwave (MW) detuning (in MHz) relative to fluorescence intensity (in arbitrary units) illustrating the principle of NV FM microwave demodulation in a device such as that described with reference to Fig. 10. The black trace shows experimentally measured optically detected magnetic resonance (ODMR) near 2.87 GHz of NV centers. The fluorescence intensity depends on the detuning of the input microwave frequency from the ODMR resonance. The carrier frequency (f_c) is positioned on the slope, and changes in microwave frequency are mapped onto the changes in fluorescence intensity.

[0066] Fig. 12 is a graph of input and output waveforms, illustrating the input FM microwave signal to be demodulated and resulting output amplitude-modulated fluorescence signal of the device of Fig. 10.

[0067] The schematic of an NV radio receiver is depicted in Fig. 10. It is based on a bulk diamond sample (*e.g.*, Element Six, HPTP diamond plate, with f100g faces) with a high density of NV centers (*e.g.*, ~1.2 ppm with nitrogen concentration about 200–300 ppm, determined by absorption techniques). The diamond sample is irradiated with 4.5 MeV electrons for 2 h, annealed at 800 °C for 16 h, and then at 1200 °C for 2 h. The diamond chip is continuously excited by a green (532 nm) laser; the excitation light spot is about 20 mW illuminating a 200- μ m-diameter region at the surface of the diamond sample. An electromagnet is used to provide a dc magnetic field along axes of one NV class that defines the carrier frequency that the diamond receiver responds to. The microwave signal is delivered to the diamond chip by a microstrip waveguide 1007 contacting the surface of the diamond. The microstrip is microfabricated on a cover glass with a 20- μ m width. The NV fluorescence, the output of the radio receiver, is collected by an objective (*e.g.*, Olympus SLMPlan 50X/NA 0.35) and detected by a photodetector (*e.g.*, New Focus 1801-FS) with

filters (*e.g.*, Semrock StopLine notch filter 532 nm, E grade, and Semrock EdgeBasic long-wavelength-pass filter, 632.8 nm). The continuous optical pumping enables the continuous detection of the input microwave signal and enjoys the benefits of the high density of NV centers in bulk diamond. The high NV density gives a greater signal intensity and thus a better signal-to-noise ratio, even though the coherent time of dense NV centers could be shorter than the scattered NV centers in bulk diamond.

[0068] The FM discrimination in the device of **Fig. 10** is achieved by the electron-spin-state-dependent fluorescence of NV centers. The negatively charged NV center is a lattice defect in diamond, which consists of a substitutional nitrogen atom and an adjacent vacancy. The ground state of the NV center is a spin triplet state, and the $m_s = \pm 1$ sublevels can be distinguished by their darker photoluminescence than the $m_s = 0$ sublevel due to the spin-selective intersystem crossing. For clarity and simplicity, the present disclosure describes the interaction between $m_s = -1$ and $m_s = 0$ sublevels. The sublevels in ground states are separated by Equation 2, where $D(T)$ is the crystal field splitting depending on the temperature T , which is about 2.87 GHz at room temperature, the gyromagnetic ratio $\gamma/2\pi$ of NV centers is 28 MHz/mT, B_0 is the dc magnetic field projected on the NV axis.

$$f_0 = D(T) - \gamma B_0$$

Equation 2

[0069] As shown in **Fig. 11**, when the microwave frequency f_{mw} is swept over the resonance frequency f_0 of the NV ground sublevels, a dip in fluorescence intensity is observed. The principle of demodulating the FM microwave signal is as follows: when the carrier frequency is positioned on the slope of the dip, the frequency of the microwave signal is mapped onto the intensity modulation of the NV fluorescence. The optical (fluorescence) response of diamond chip exposed to an FM (square wave) microwave signal is depicted in **Fig. 12**.

[0070] Referring now to Figs. 13-15, graphs are provided of original signals and signals received through a device such as described above with reference to Fig. 10. The demodulated fluorescence intensities (shown in lower curves) are compared to the original modulating signal (shown in upper curves). The curves are offset for clarity. Fig. 13 illustrates a 1 kHz sine wave. Fig. 14 illustrates a 1 kHz square wave. Fig. 15 illustrates an audio signal. The carrier microwave is at 2.85 GHz. In each case, the original signal is displayed above the demodulated signal.

[0071] Reception of FM radio signals carried by a 2.85-GHz carrier using the diamond NV centers is demonstrated. A known modulating signal (provided by a waveform generator, *e.g.*, Agilent 33120A) representing the information is sent to a microwave function generator (*e.g.*, HP ESG-3000A) to generate an FM microwave signal at the carrier frequency of 2.85 GHz with -3 dBm power. The microwave signal is then sent to the NV centers via a microstrip. The red fluorescence of NV centers is filtered, detected, and monitored by an oscilloscope with the modulating signal, as shown in Figs. 13-15. A dc magnetic field is applied by the electromagnet to shift the optically detected magnetic resonance (ODMR) dip to the position so that the carrier frequency is blue detuned from the NV microwave resonance. In this way, the received signal is in phase with the original modulating signal. From Figs. 13-14, it may be seen that the received signals are in good agreement with the modulating signals. As a demonstration of a real-life application, as shown in Fig. 15, a received audio waveform is also in good agreement with the original audio waveform.

[0072] Referring now to Fig. 16, a graph is provided of optical response (dB) relative to modulating frequency (Hz), illustrating the optical response of an NV radio receiver on the frequency of modulating signals. The solid line is measured by the lock-in amplifier, and the dashed line is measured by the network analyzer. Lines of different color correspond to different carrier microwave powers indicated in the inset. In particular, line 1601

corresponds to power 1611, line 1602 corresponds to power 1612, line 1603 corresponds to power 1603, and line 1604 corresponds to power 1604. The inset illustrates the dependency of -3 dB optical bandwidth on the powers of input microwave signals.

[0073] Fig. 17 is a histogram of the harmonic distortion of the output fluorescence intensity in the case of a 1-kHz sine wave as a modulating signal with a maximum frequency deviation of $\Delta = 2.42$ MHz. The power of the microwave signal is -5 dBm.

[0074] The frequency responses of the NV radio of Fig. 10 is characterized for various microwave signal powers in Fig. 16. The modulating frequency of the carrier microwave signal is swept from 10 Hz to 3 MHz. Because of the limitation of detecting frequencies of the equipment, the 10-to-100-kHz response is measured by a lock-in amplifier (*e.g.*, Stanford SR830), and are represented by solid lines in Fig. 16. The 30-kHz-to-30-MHz frequencies are measured by a network analyzer (*e.g.*, HP 8753E), and are represented by dashed lines in Fig. 16. The modulating signal is a sine wave with peak-to-peak amplitude $V_{pp} = 1$ V, and leads to the maximum deviation of 1 MHz from the frequency of the carrier microwave. As shown in Fig. 16, the -3 -dB bandwidth of optical response is measured as 91.8 kHz with a microwave signal of 0 dBm (1 mW), which is the maximum power that the microstrip of this exemplary embodiment can carry before being damaged. The carrier microwave frequency sits at the maximum slope of resonance dip, ensuring an optimum amplitude of the demodulated signal, as shown in Fig. 11.

[0075] This bandwidth is adequate for high-fidelity audio transmission, as shown in Fig. 15. The bandwidth of the NV radio receiver is sensitive to the power of the input microwave signal. As plotted in Fig. 16, inset, the bandwidth is lowered from 91.8 to 22.5 kHz when microwave signal power is attenuated from 0 to -10 dBm. The bandwidth also depends on other parameters including the pumping (green) laser power and detuning of the microwave carrier. A useful approximation is that greater pumping laser powers and microwave signal

powers result in greater bandwidths. The bandwidth may be extended by detuning of the carrier microwave from ODMR. However, the amplitude of the fluorescence signal suffers when the microwave frequency is detuned beyond one linewidth of the NV ground-state sublevels. The bandwidth of NV centers may be extended by changing the life time of states by strain.

[0076] The total harmonic distortion (THD) is 2.67% of the total signal at the microwave power of -5 dBm with a frequency deviation of 2.42 MHz, which is the half of the linewidth (as FWHM) of the NV microwave resonance in the ground state. In this case, the modulating signal is a 1-kHz sine wave, and the optical intensity (as the output of the photodetector) of the higher-order harmonic frequencies is measured by the lock-in amplifier, as shown in Fig. 17. The optical intensity of each generated harmonics is less than 1% of the fundamental signal, and the total harmonic distortion THDF (defined by the root-squared sum of all the harmonic distortion amplitude divided by the amplitude of the fundamental signal, *i.e.*, $THD_F = \sqrt{\sum_{k \geq 2} V_k^2} / V_1$, where V_k is the amplitude at kth harmonic frequency) is measured to be 2.67%. The distortion originates from the nonlinear dependence of microwave frequency and the fluorescence intensity, which is a Lorentzian dip, and thus the distortion depends on the amplitude of the input signal. This THD_F level is acceptable for the transmission of audio signals, as it can hardly be detected by a human ear.

[0077] Referring to Fig. 18, a graph of optical response (arbitrary units) relative to electromagnetic voltage (V) is provided, illustrating optical response on the dc magnetic field B_0 under different environmental temperatures. The magnetic field B_0 is controlled by the voltage applied on the electromagnet. The sign of the optical response indicates the polarity between the NV fluorescence signal and the modulating signal.

[0078] Referring to Fig. 19, a graph of response amplitude (arbitrary units) relative to temperature (°C) is provided, illustrating the maximum responses on the environmental

temperature. The response amplitudes of optimum negative and positive detuning correspond to the minimum and maximum points.

[0079] Referring to Fig. 20, a graph of electromagnetic voltage (V) relative to temperature (°C) is provided, illustrating the optimum electromagnetic voltages required to compensate for the temperature shifts.

[0080] Behavior of the NV radio receiver of Fig. 10 operating in environmental temperature from 25 °C (298 K) to 400 °C (673 K) is demonstrated, where the diamond sample and the microwave microstrip shown in Fig. 10 are under controlled temperatures. NV centers can operate in a wide temperature range from 6 K to 600 K. Here, as illustrated by Equation 2, the temperature affects the zero-field crystal field splitting of the NV centers. To demodulate a radio receiver with stable resonant microwave frequency under different temperatures, the magnetic field B_0 may be used to adjust to compensate the temperature effects in a feedback loop.

[0081] The NV crystal field splitting depends on the temperature T as $dD(T)/dT = -74$ kHz/K, though the exact value of the constant slightly varies between different samples with different NV densities. In various examples, the dc magnetic field is lowered to cancel out the shift caused by the higher temperature (in the case of using the $m_s = -1$ ground-state sublevel). In such cases, tuning of the dc magnetic field B_0 may be achieved by changing the voltage applied to the electromagnet. In one example, the carrier frequency of the microwave signal is fixed at 2.80 GHz, the modulating signal is a 1-kHz sine wave, and the maximum frequency deviation is set to 2 MHz. As shown in Fig. 18, the output signal is measured under different applied electromagnet voltages and temperatures. The sign of the output signal indicates the phase relative to the modulating signal. This demonstrates that the optimum external magnetic field B_0 changes as the temperature changes, as shown in

Fig. 20. In addition, the signal maximum reduces as the temperature increases, as shown in **Fig. 19.**

[0082] Accordingly, NV radio receivers according to the present disclosure operate up to at least 350 °C (628 K), although the amplitude of the received signal may suffer at high temperatures. At 350 °C, the amplitude of the signal is only one tenth of that at room temperature. This can be explained by the dynamics of NV centers. At high temperatures, the thermally activated nonradiative processes diminish the spin selectivity of the excited state intersystem crossing and the spin-dependent fluorescence vanishes out.

[0083] In various embodiments of the present disclosure, a radio receiver based on NV centers in diamonds is provided that is capable of demodulating an FM microwave signal and mapping it onto an amplitude-modulated fluorescent signal. In various embodiments, the radio is tuned via a dc magnetic field, provided by an electromagnet, which selects the carrier frequency. The robustness of diamond NV centers enables operation at temperatures at least as high as 350 °C.

[0084] In some embodiments, the required microwave power and the bandwidth of the NV centers as a transducer may be improved by providing resonant microwave circuits for specific applications or frequencies. The excitation and collection of NV fluorescence may be enhanced by photonic structures as well. In alternative embodiments, other atomic defects in solids can be used to realize radio receivers (or wavelength converters) in the frequency bands of interest to modern communications and quantum information processing. For example, silicon vacancy centers in diamond are suitable for microwave-to-optical converters in the terahertz band, and the resonant microwave frequency can be tuned by strain.

[0085] The descriptions of the various embodiments of the present invention have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the

embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments. The terminology used herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments disclosed herein.

CLAIMS

What is claimed is:

1. A device, comprising:
 - a substrate, comprising at least a first region having a plurality of atomic defects therewithin;
 - a light source configured to emit electromagnetic radiation of a first wavelength and to illuminate the first region of the substrate, said first region emitting electromagnetic radiation of a second wavelength when exposed to electromagnetic radiation of the first wavelength; and
 - a photodetector configured to detect electromagnetic radiation of the second wavelength, said photodetector configured to detect electromagnetic radiation emitted by the first region of the substrate.
2. The device of Claim 1, wherein
 - the first region of the substrate is adapted to be exposed to a frequency-modulated electromagnetic input having a wavelength range, and wherein
 - the intensity of the electromagnetic radiation emitted by the first region of the substrate, when illuminated by the light source, varies substantially linearly with the frequency of the frequency-modulated electromagnetic input.
3. The device of claim 1, further comprising:
 - a magnetic field source configured to expose the first region of the substrate to a magnetic field and thereby to tune the first region of the substrate to the wavelength range of the frequency-modulated electromagnetic input.
4. The device of claim 3, wherein the magnetic field source is tunable.
5. The device of claim 2, wherein the first region of the substrate is tuned to the wavelength range of the frequency-modulated electromagnetic input.
6. The device of claim 5, wherein the wavelength range of the frequency-modulated electromagnetic input is from about 300 MHz to about 300 GHz.
7. The device of claim 1, wherein the substrate comprises a crystalline solid.
8. The device of claim 1, wherein the substrate comprises diamond.
9. The device of claim 1, wherein the substrate comprises crystalline silicon.
10. The device of claim 1, wherein the plurality of atomic defects comprises nitrogen-vacancy centers.

11. The device of claim 1, wherein the plurality of atomic defects comprises silicon vacancy centers.
12. The device of claim 1, wherein the light source comprises a laser.
13. The device of claim 1, wherein the first wavelength is about 532 nm.
14. The device of claim 1, wherein the first region of the substrate has a characteristic size of about 200 μm .
15. The device of claim 1, wherein the second wavelength is about 632 nm.
16. The device of claim 1, wherein the first region has a surface area of about 100 μm^2 .
17. The device of claim 1, wherein the plurality of atomic defects has a density of about 10^{17} cm^{-3} to about $2 \times 10^{17} \text{ cm}^{-3}$ within the substrate.
18. The device of claim 1, wherein the light source is configured to illuminate about 10^7 atomic defects.
19. A method of detecting a frequency-modulated wave, the method comprising:
 - exposing a device to a frequency-modulated electromagnetic input having a wavelength range, the device comprising
 - a substrate, comprising at least a first region having a plurality of atomic defects therewithin,
 - a light source configured to emit electromagnetic radiation of a first wavelength and to illuminate the first region of the substrate, said first region emitting electromagnetic radiation of a second wavelength when exposed to electromagnetic radiation of the first wavelength, and
 - a photodetector configured to detect electromagnetic radiation of the second wavelength, said photodetector configured to detect electromagnetic radiation emitted by the first region of the substrate;
 - directing electromagnetic radiation of the first wavelength emitted by the light source to the first region of the substrate, thereby causing the first region of the substrate to emit electromagnetic radiation of the second wavelength; and
 - detecting by the photodetector electromagnetic radiation emitted by the first region of the substrate.
20. The method of Claim 19, wherein the intensity of the electromagnetic radiation emitted by the first region of the substrate, when illuminated by the light source, varies substantially linearly with the frequency of the FM input.
21. The method of claim 19, further comprising:

- exposing the first region of the substrate to a magnetic field, thereby tuning the first region of the substrate to the wavelength range of the frequency-modulated electromagnetic input.
22. The method of claim 19, wherein the wavelength range of the frequency-modulated electromagnetic input is from about 300 MHz to about 300 GHz.
23. The method of claim 19, wherein the substrate comprises a crystalline solid.
24. The method of claim 19, wherein the substrate comprises diamond.
25. The method of claim 19, wherein the substrate comprises crystalline silicon.
26. The method of claim 19, wherein the plurality of atomic defects comprises nitrogen-vacancy centers.
27. The method of claim 19, wherein the plurality of atomic defects comprises silicon vacancy centers.
28. The method of claim 19, wherein the light source comprises a laser.
29. The method of claim 19, wherein the first wavelength is about 532 nm.
30. The method of claim 19, wherein the first region has a characteristic size of about 200 μm .
31. The method of claim 19, wherein the second wavelength is about 632 nm.
32. The method of claim 19, wherein the first region has a surface area of about 100 μm^2 .
33. The method of claim 19, wherein the plurality of atomic defects has a density of about 10^{17} cm^{-3} to about $2 \times 10^{17} \text{ cm}^{-3}$ within the substrate.
34. The method of claim 19, wherein the light source is configured to illuminate about 10^7 atomic defects.
35. An apparatus for demodulating an input electromagnetic wave, the apparatus comprising:
- a substrate including atomic defects;
 - a magnetic field source;
 - an optical wave source; and
 - an electromagnetic wave detector, wherein
 - an intensity of a magnetic field provided by the magnetic field source is configured to provide a detuning of a resonance in an interaction between the input electromagnetic wave and fluorescence excited by an optical wave provided by the optical wave source, such that an intensity of an output fluorescence signal detected by the electromagnetic wave detector is

approximately linearly dependent on a frequency of the input electromagnetic wave.

36. The apparatus of claim 35, wherein the substrate comprises a crystalline solid.
37. The apparatus of claim 35, wherein the atomic defects comprise point defects.
38. The apparatus of claim 37, wherein the point defects comprise vacancy defects.
39. The apparatus of claim 38, wherein the substrate comprises diamond and the vacancy defects comprise Nitrogen vacancy centers.
40. The apparatus of claim 35, wherein the optical wave source comprises a laser.
41. The apparatus of claim 35, wherein the magnetic field source is configured to provide a static magnetic field with an intensity that is tunable over a range.
42. An apparatus comprising:
 - a magnetic field source;
 - an optical wave source; and
 - a demodulator configured to receive a static magnetic field from the magnetic field source and an optical wave from the optical wave source within a diamond substrate that includes Nitrogen-vacancy centers, and to demodulate a frequency modulated input electromagnetic wave to provide an intensity variation on an output fluorescence signal.
43. An apparatus for demodulating an input electromagnetic wave, the apparatus comprising:
 - an optical wave source; and
 - a demodulator configured to provide an output optical signal in response to the input electromagnetic wave interacting within a substrate that receives an optical wave from the optical wave source and responds to the optical wave by exciting states of atomic defects within the substrate to at least two excited states that include a first excited state and a second excited state, wherein the first excited state includes a non-radiative pathway that is not as strong for the second excited state as for the first excited state, and an intensity of the output optical signal is approximately linearly dependent on a frequency of the input electromagnetic wave.
44. A method for demodulating an input electromagnetic wave, the method comprising:
 - applying a magnetic field to a first portion of a substrate;
 - applying an optical wave to the first portion of the substrate;
 - receiving the input electromagnetic wave into the first portion of the substrate; and

detecting an intensity of an output fluorescence signal from the substrate, wherein atomic defects in the first portion of the substrate provide an interaction between the input electromagnetic wave and fluorescence exited by the optical wave, such that frequency modulation of the input electromagnetic wave is converted to intensity variation of the output fluorescence signal.

45. The method of claim 44, wherein applying the magnetic field includes selecting an intensity of the magnetic field to provide a detuning of a resonance in the interaction, such that the detected intensity of the output fluorescence signal is approximately linearly dependent on a frequency of the input electromagnetic wave.

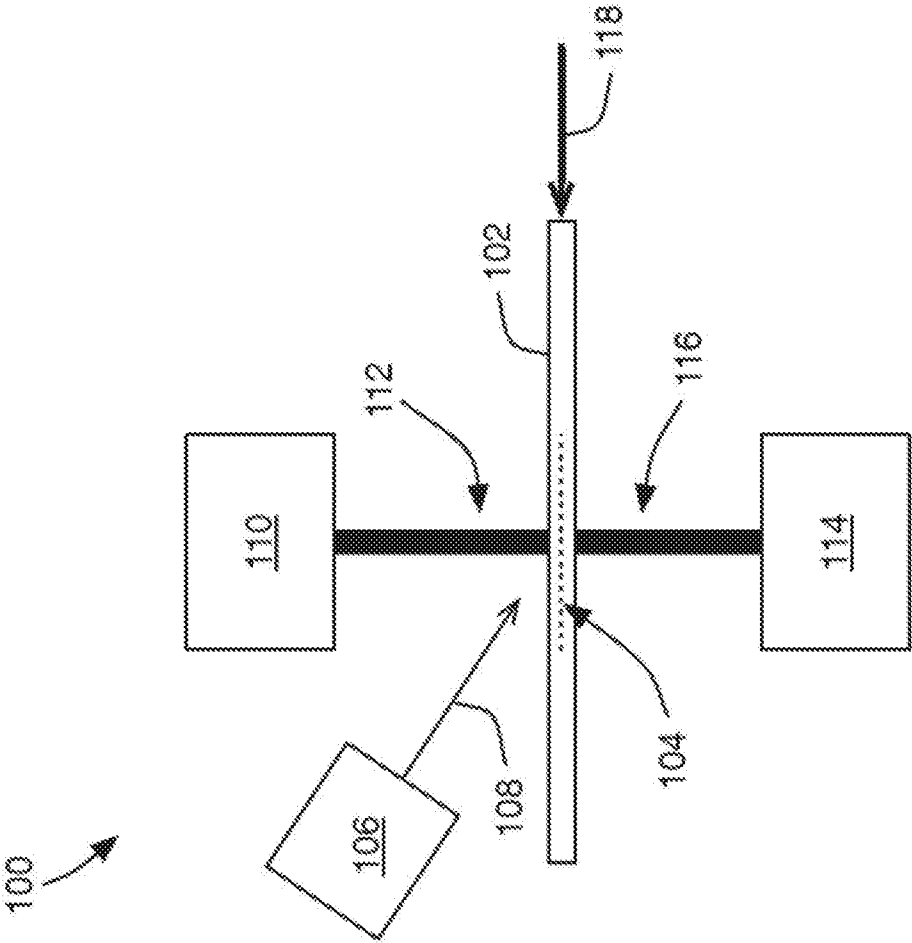


Fig. 1

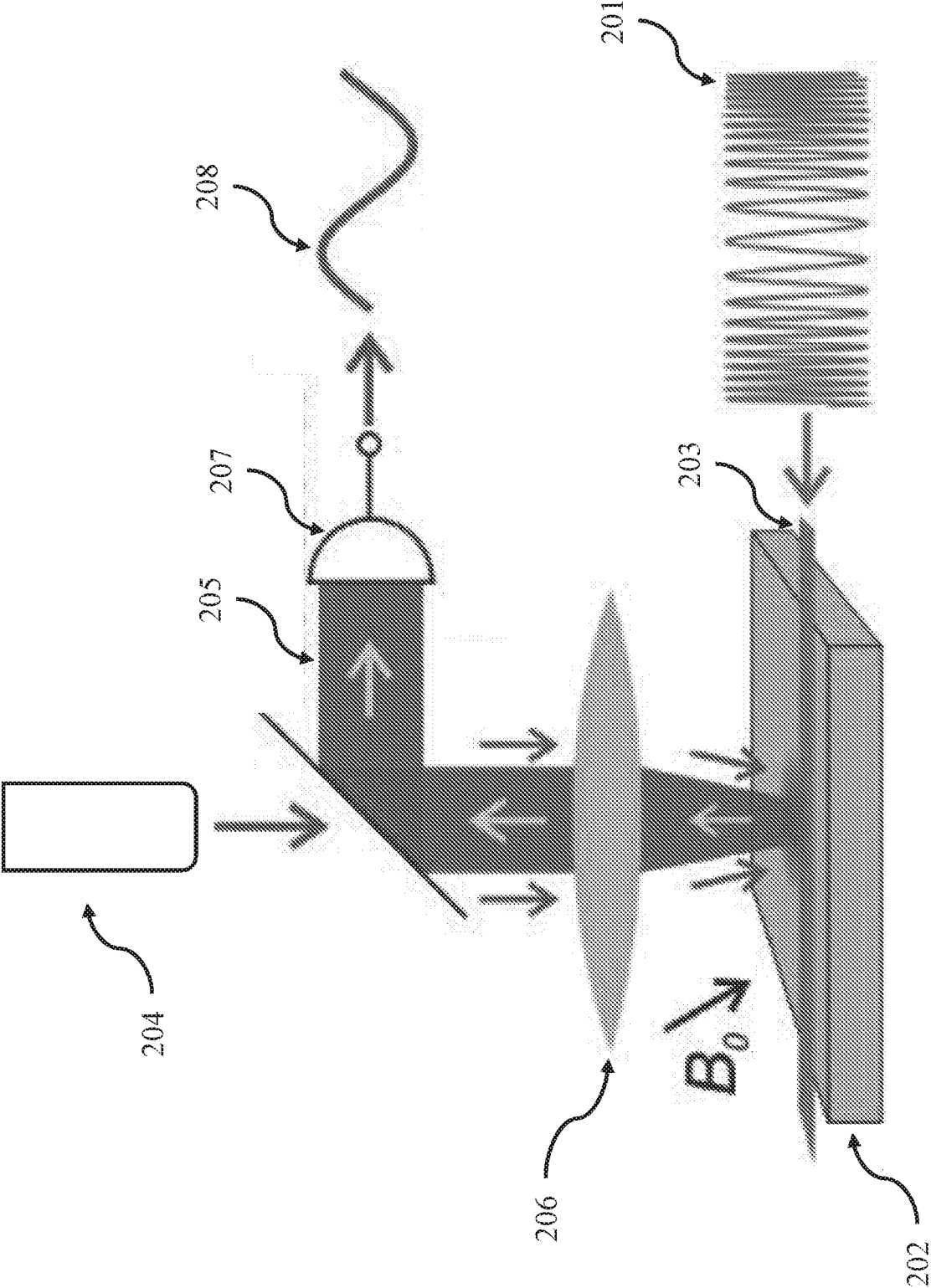


Fig. 2

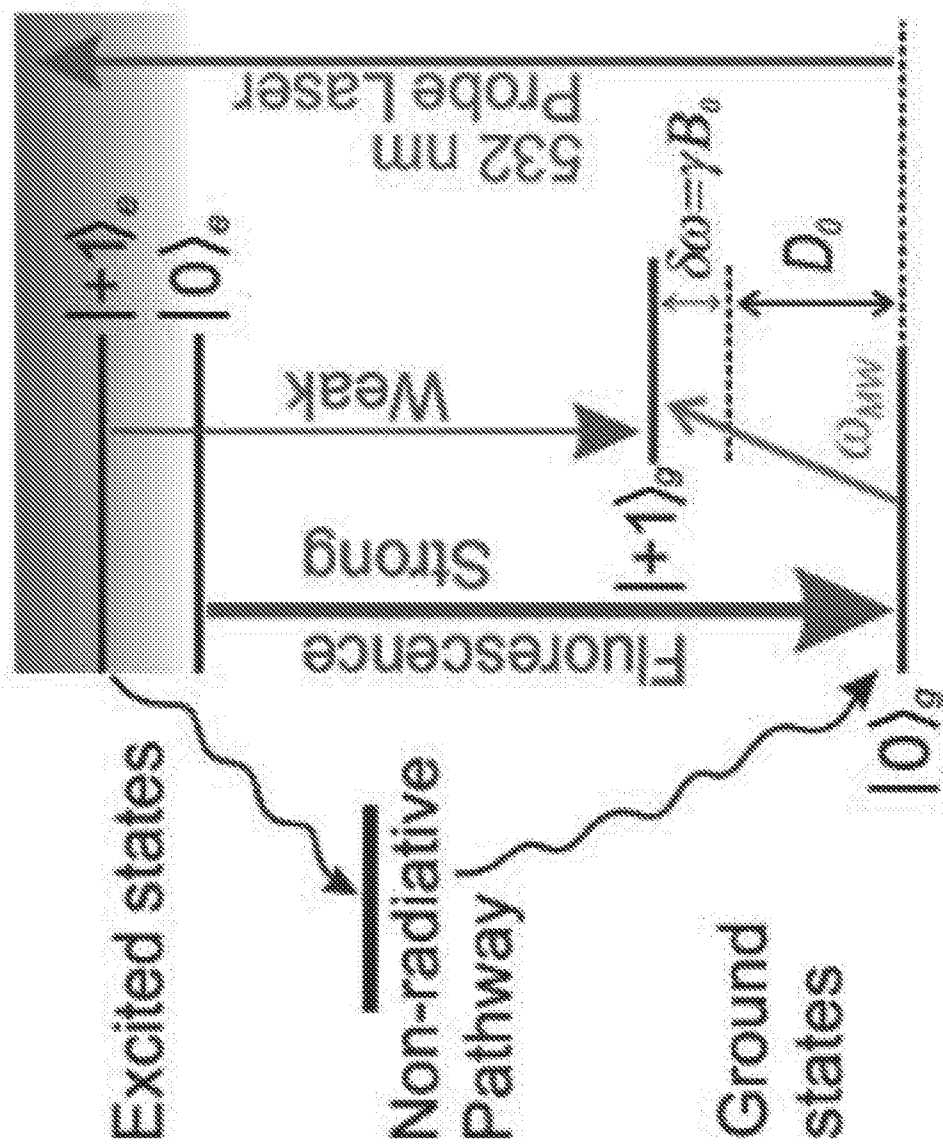


Fig. 3

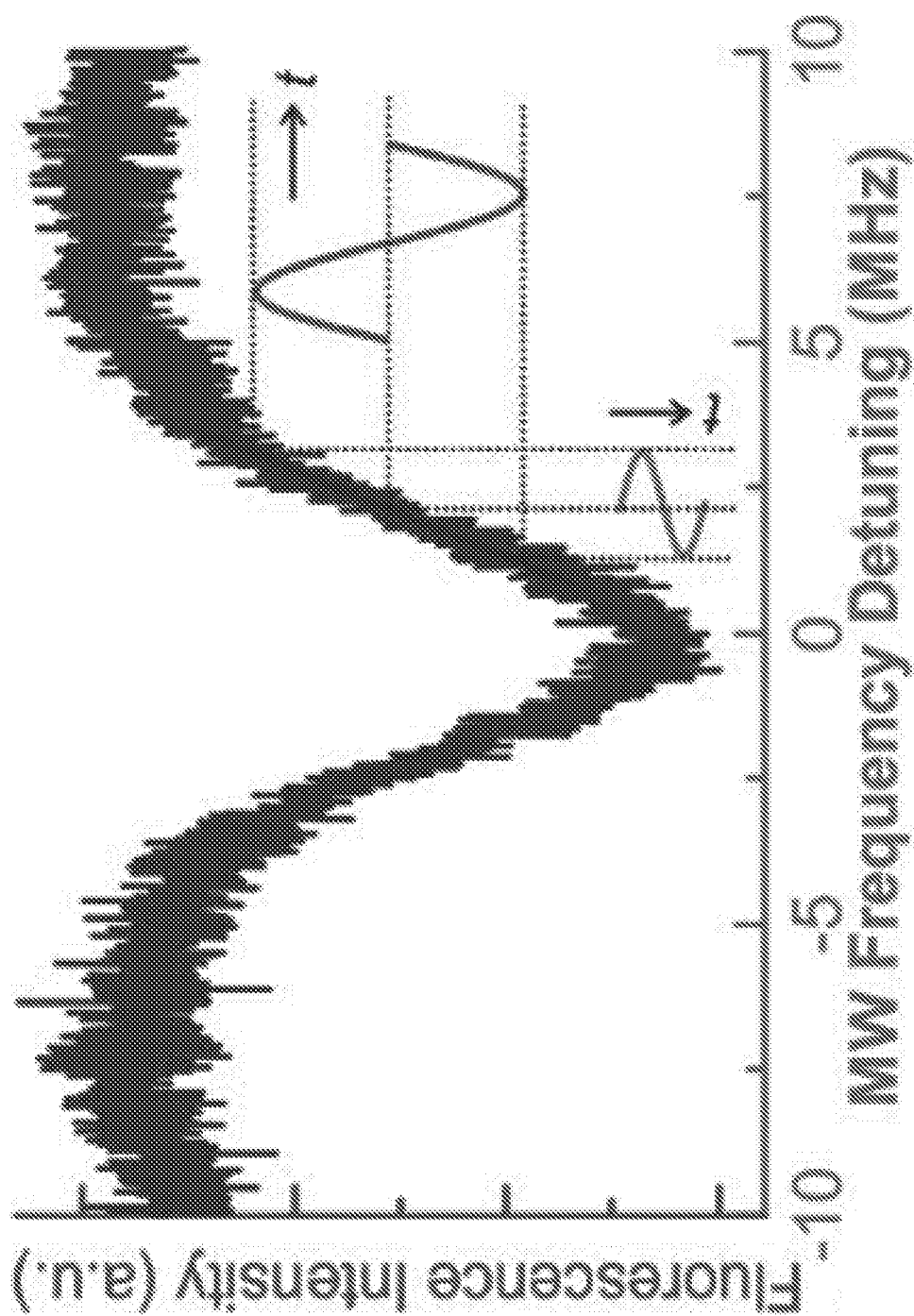


Fig. 4

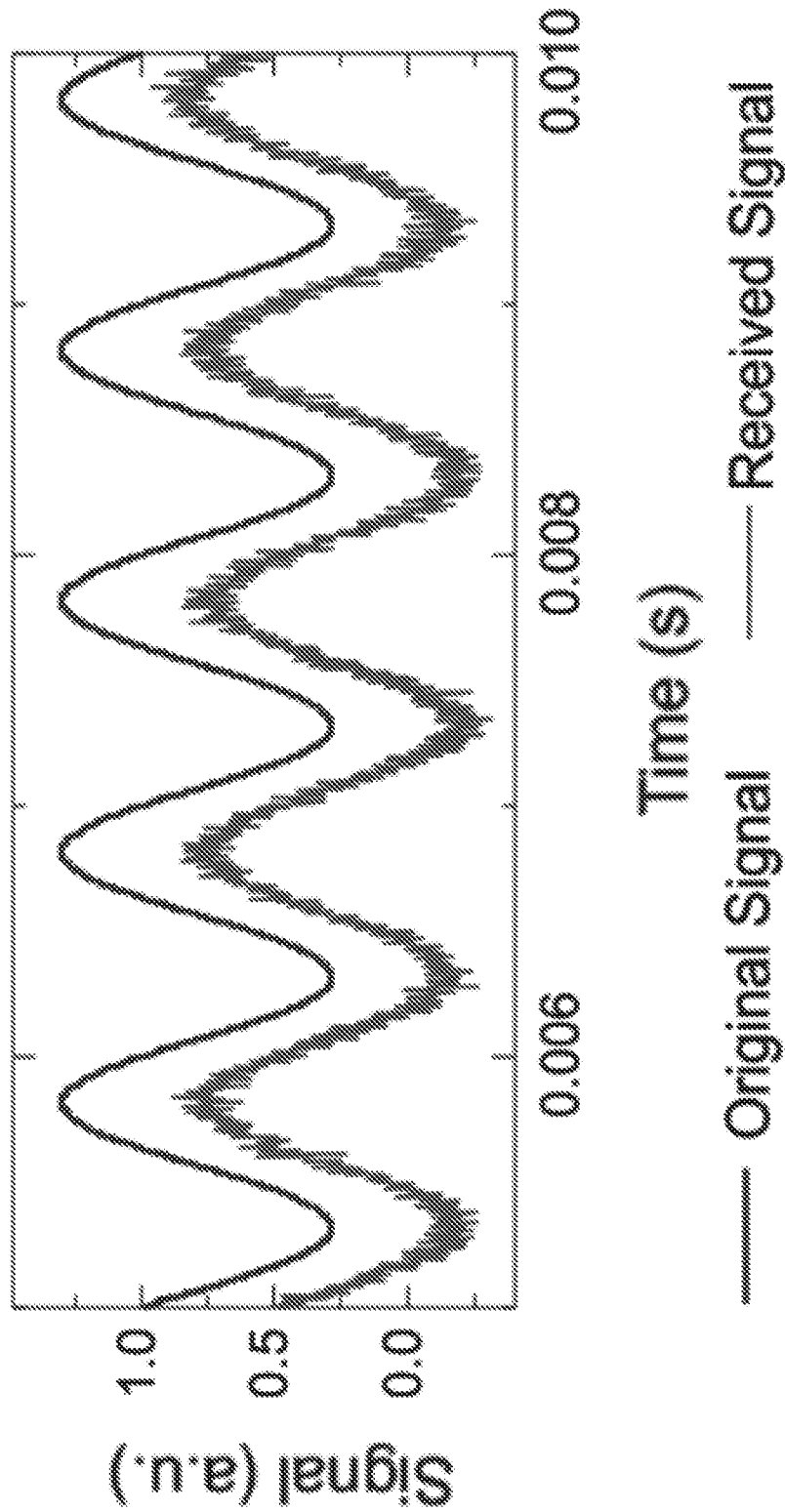


Fig. 5

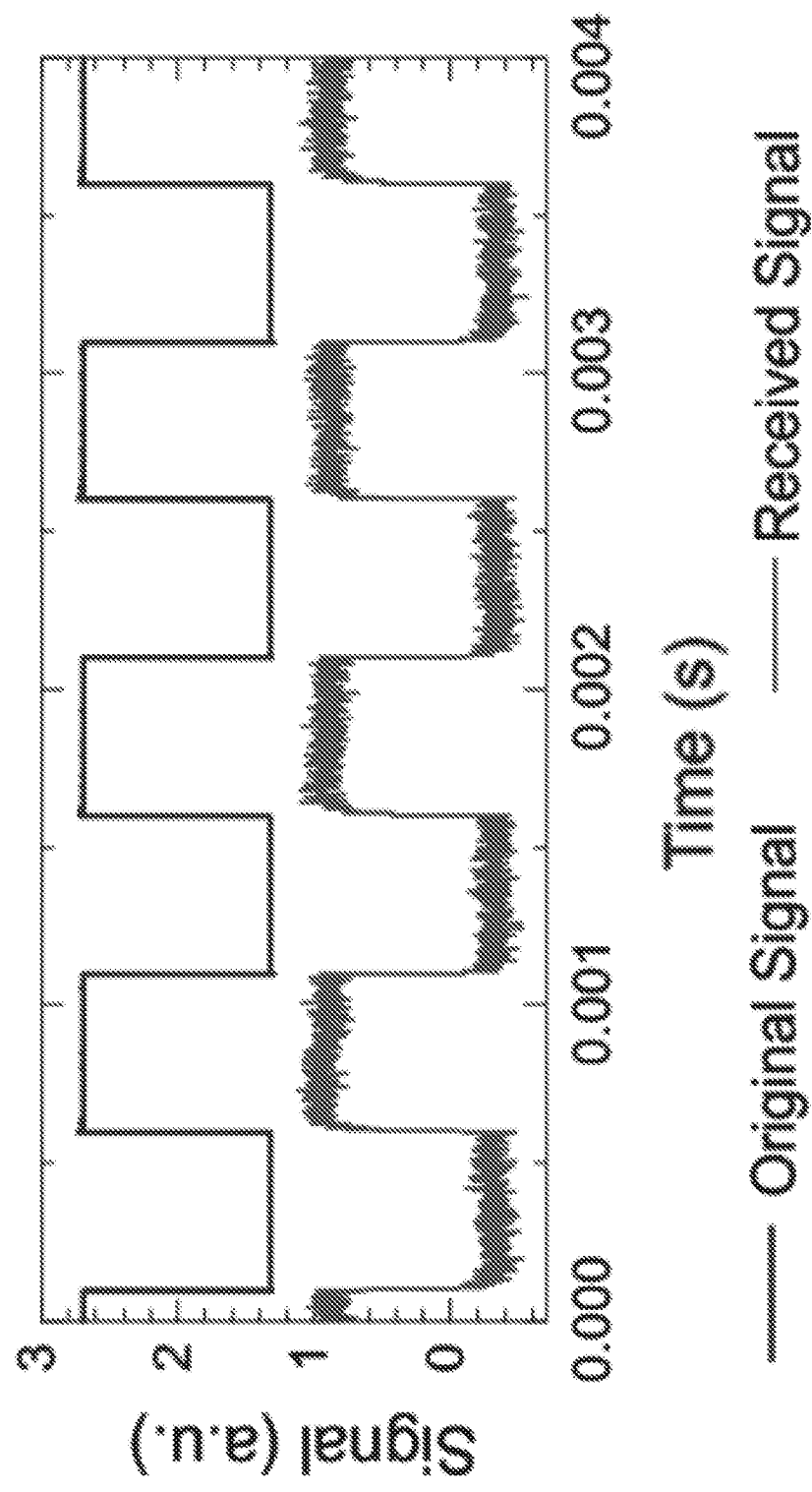


Fig. 6

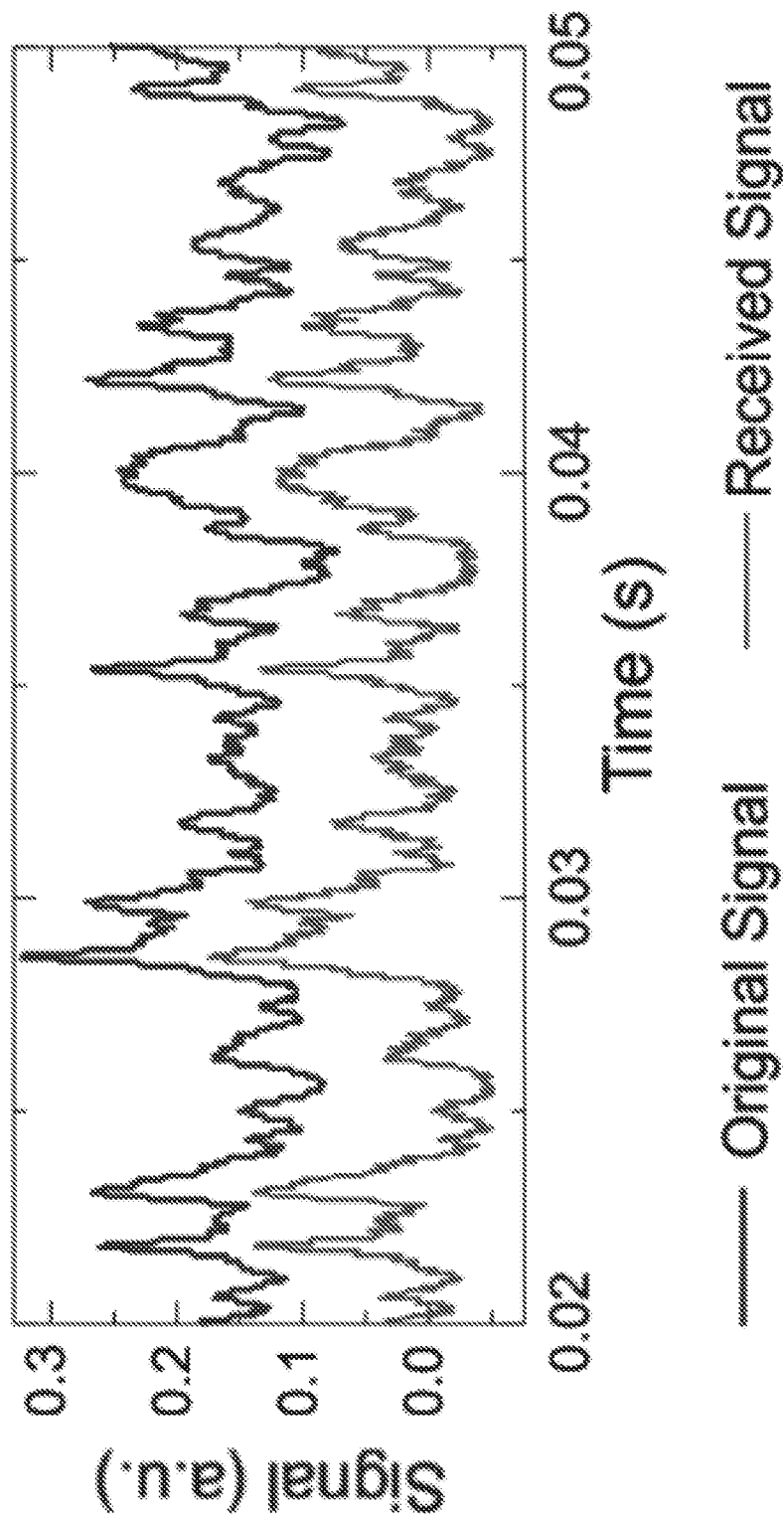


Fig. 7

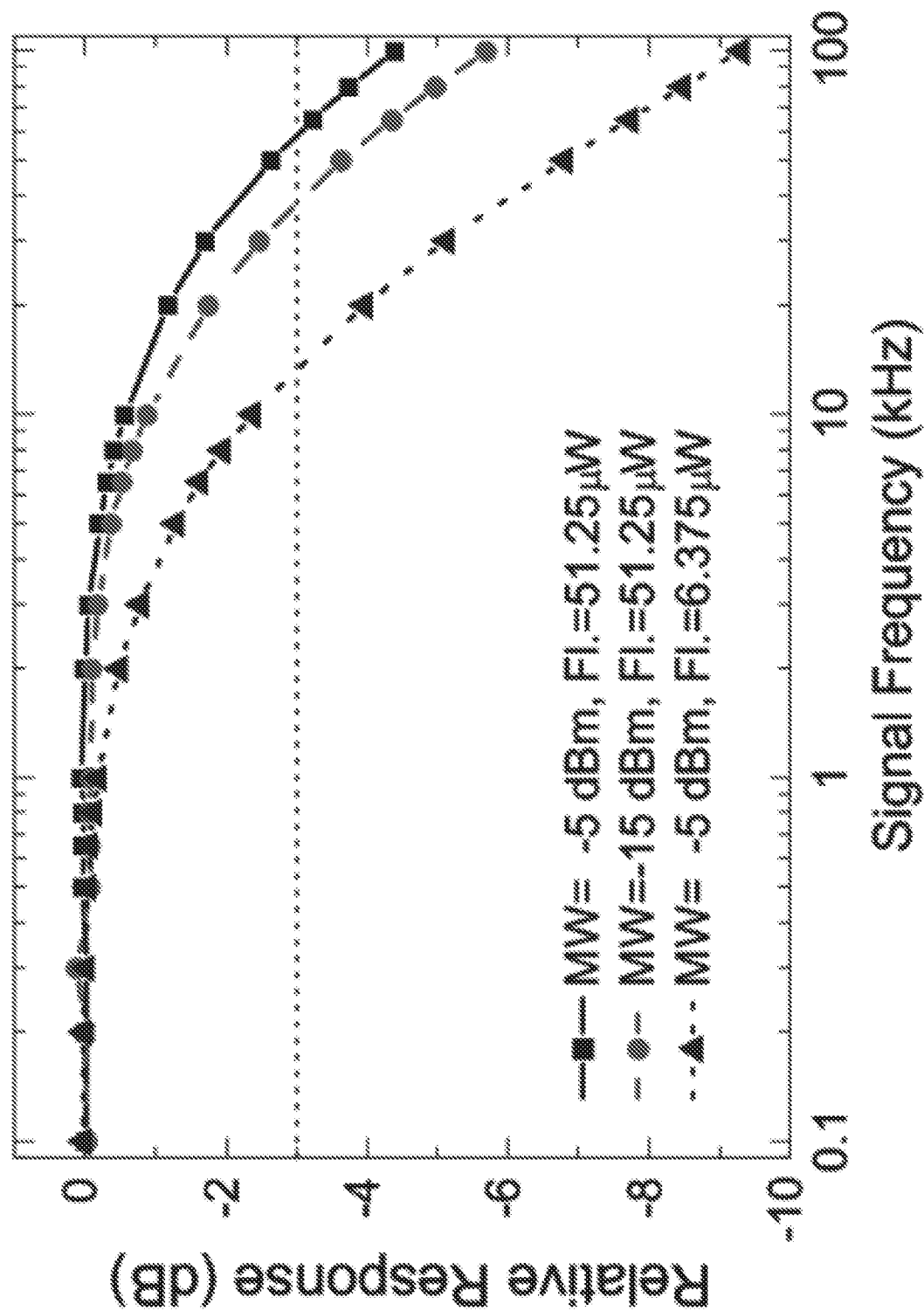


Fig. 8

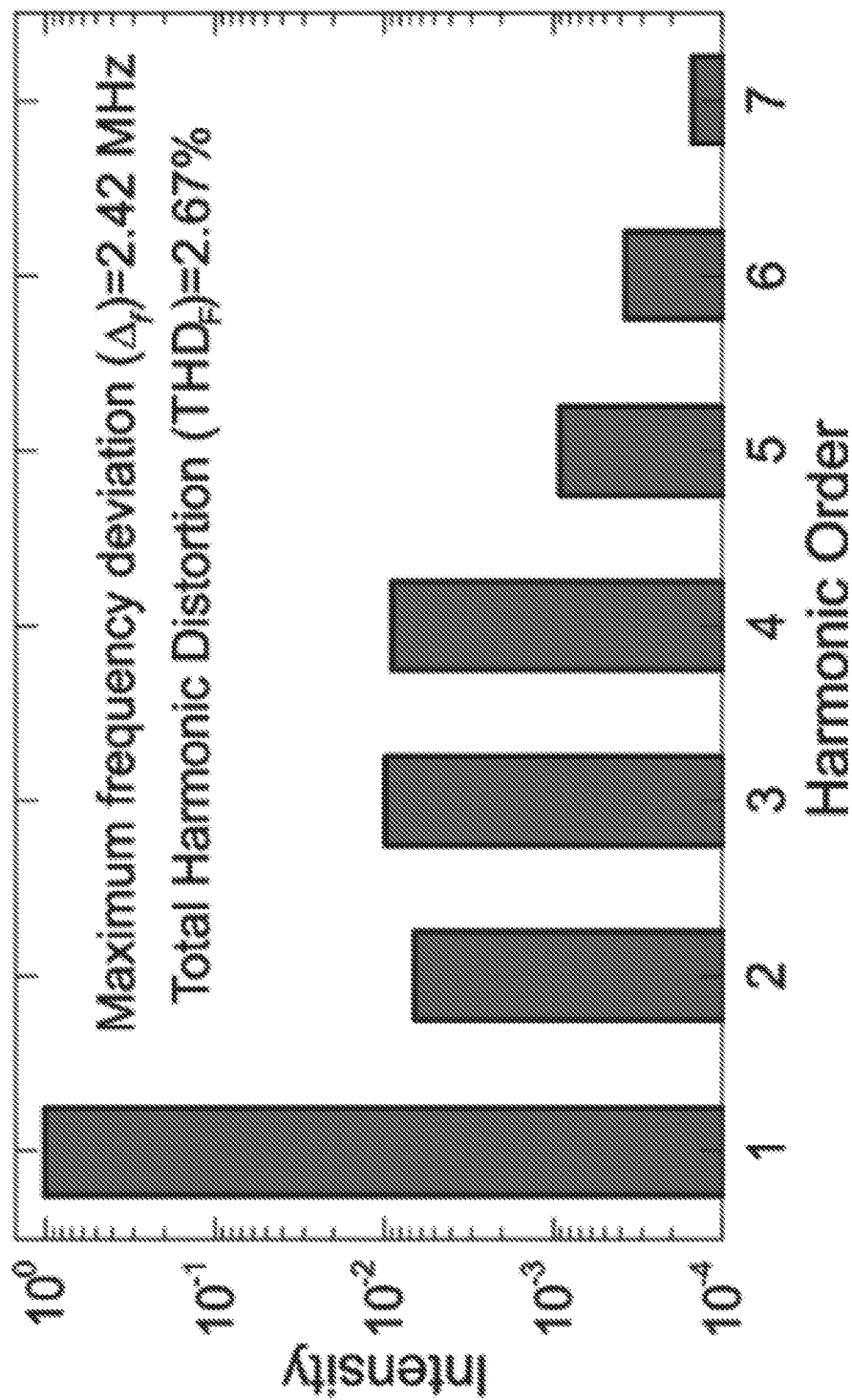


Fig. 9

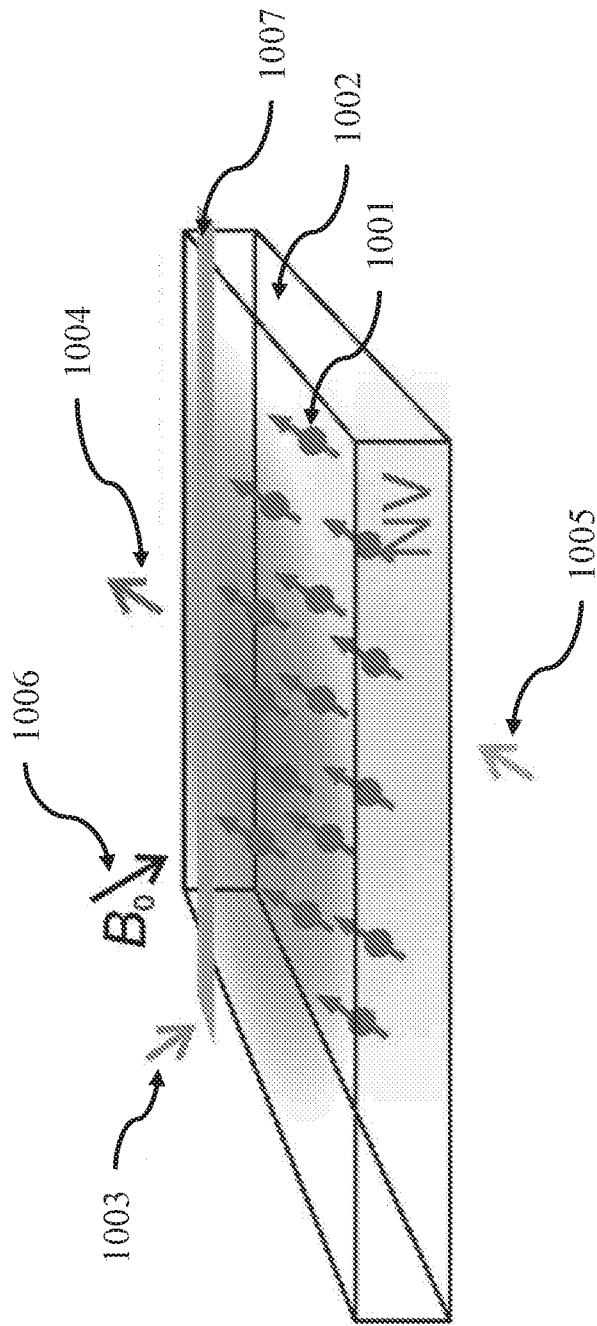


Fig. 10

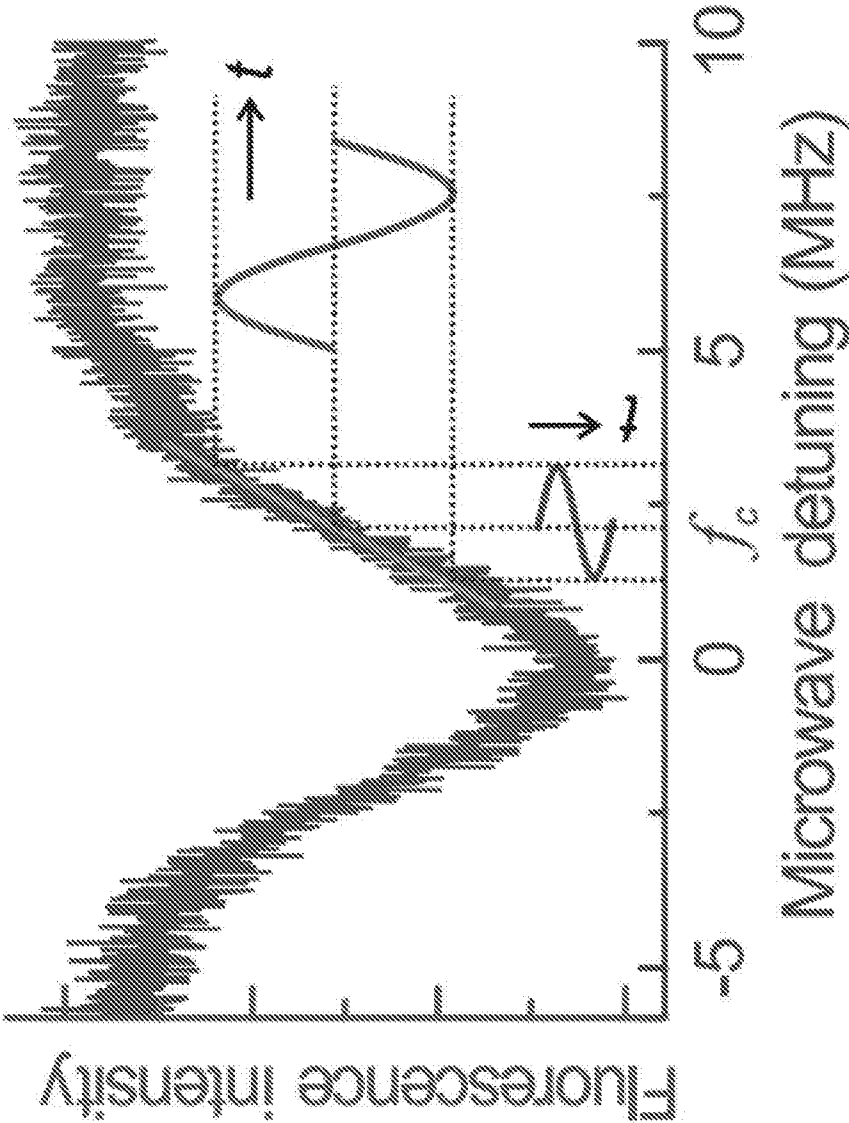


Fig. 11

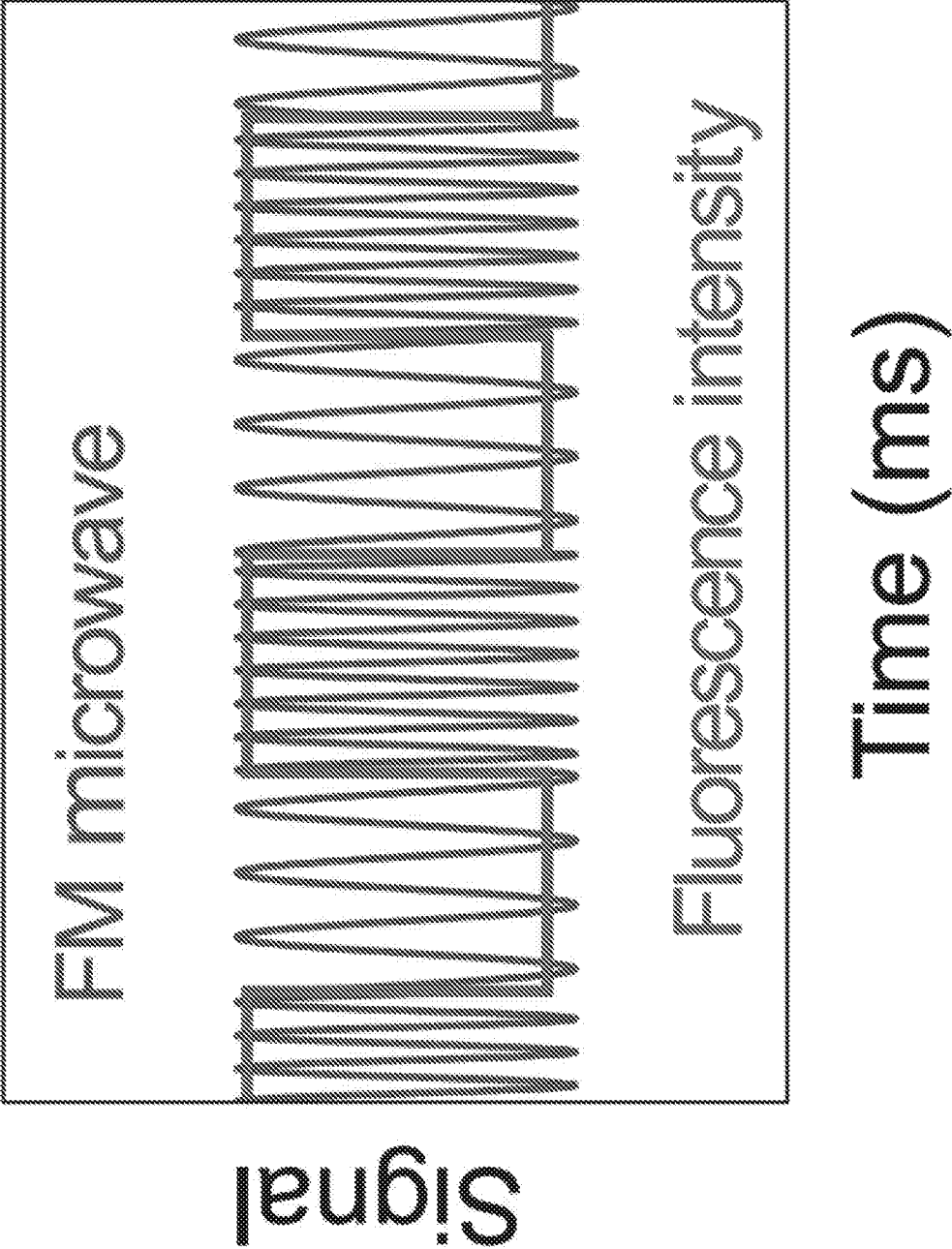


Fig. 12

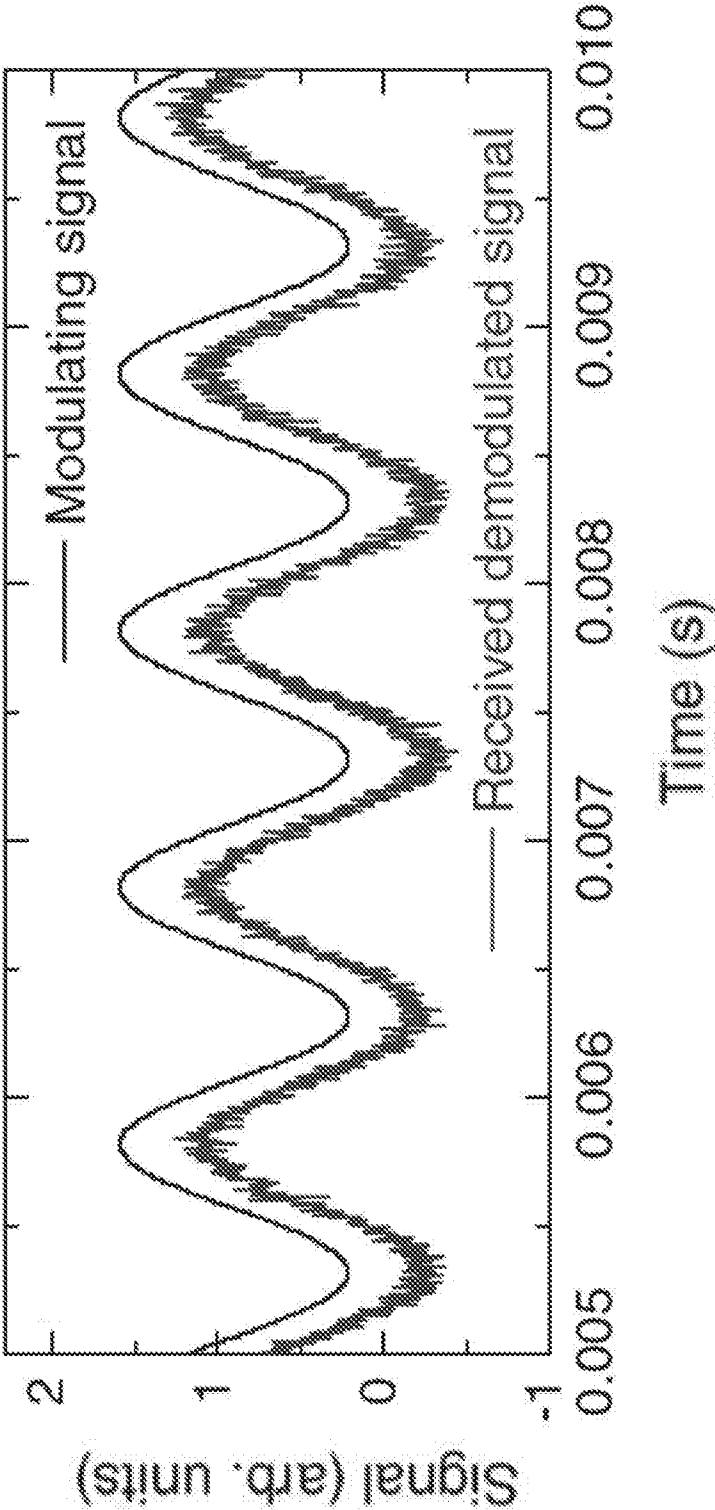


Fig. 13

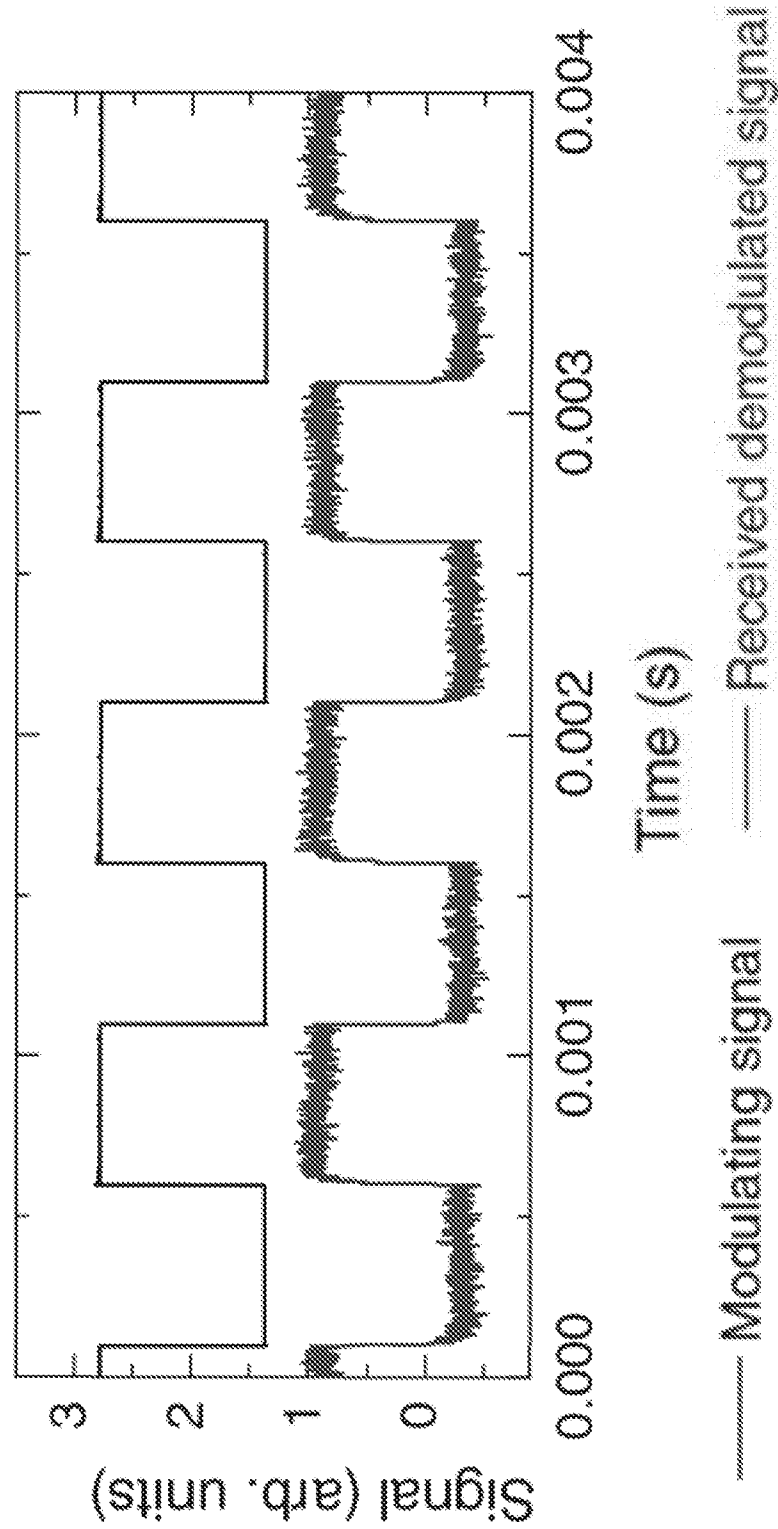


Fig. 14

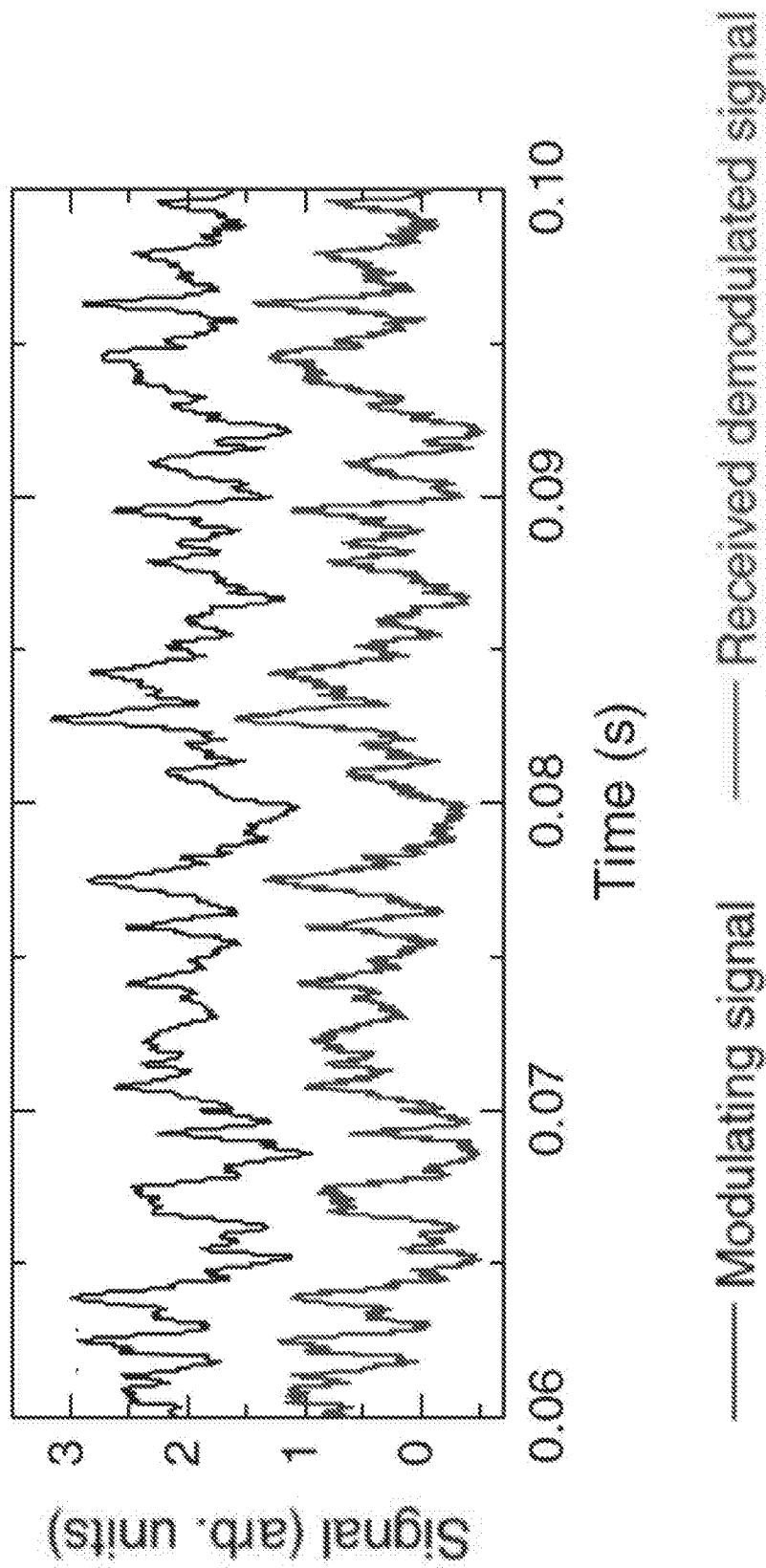


Fig. 15

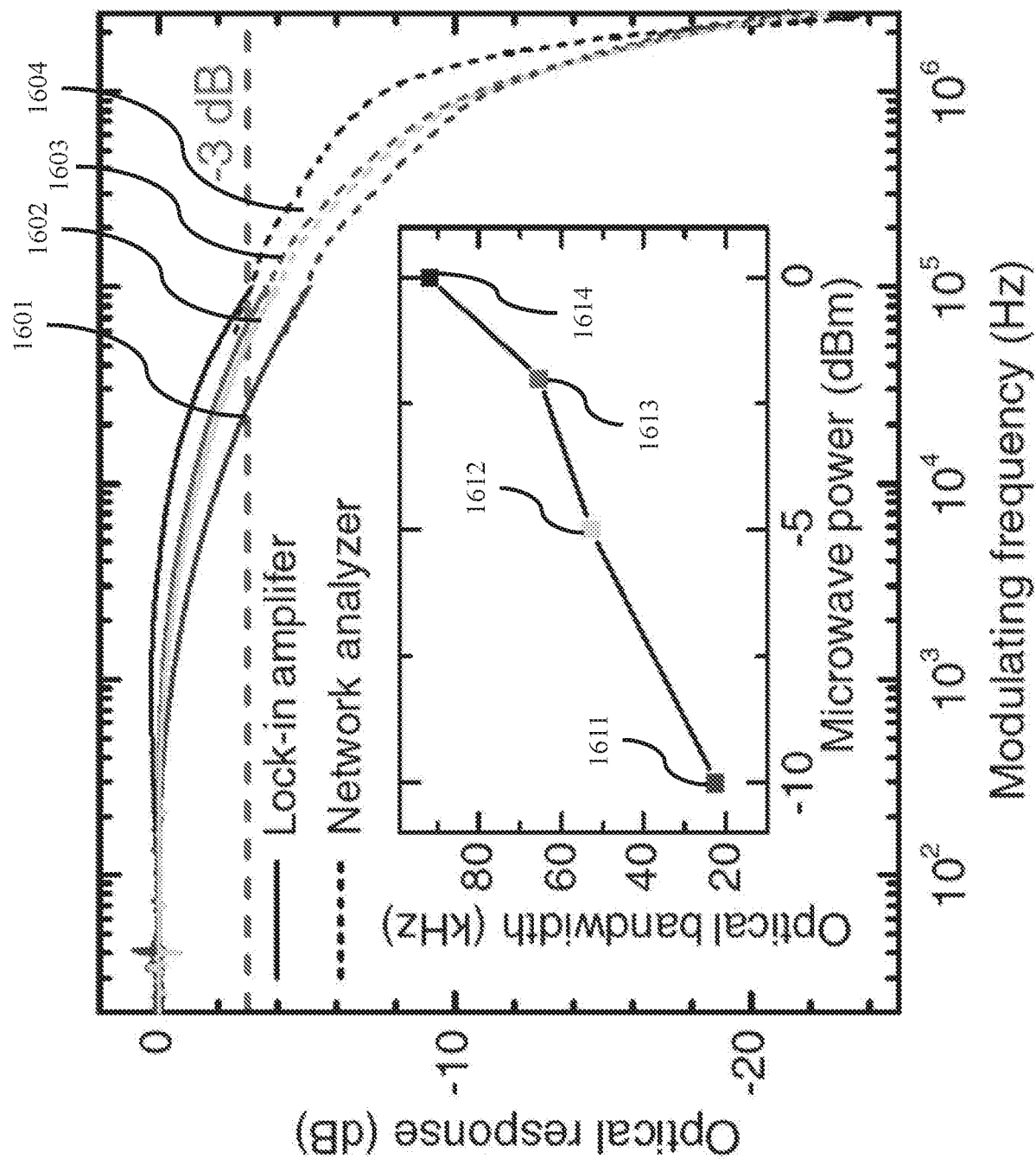


Fig. 16

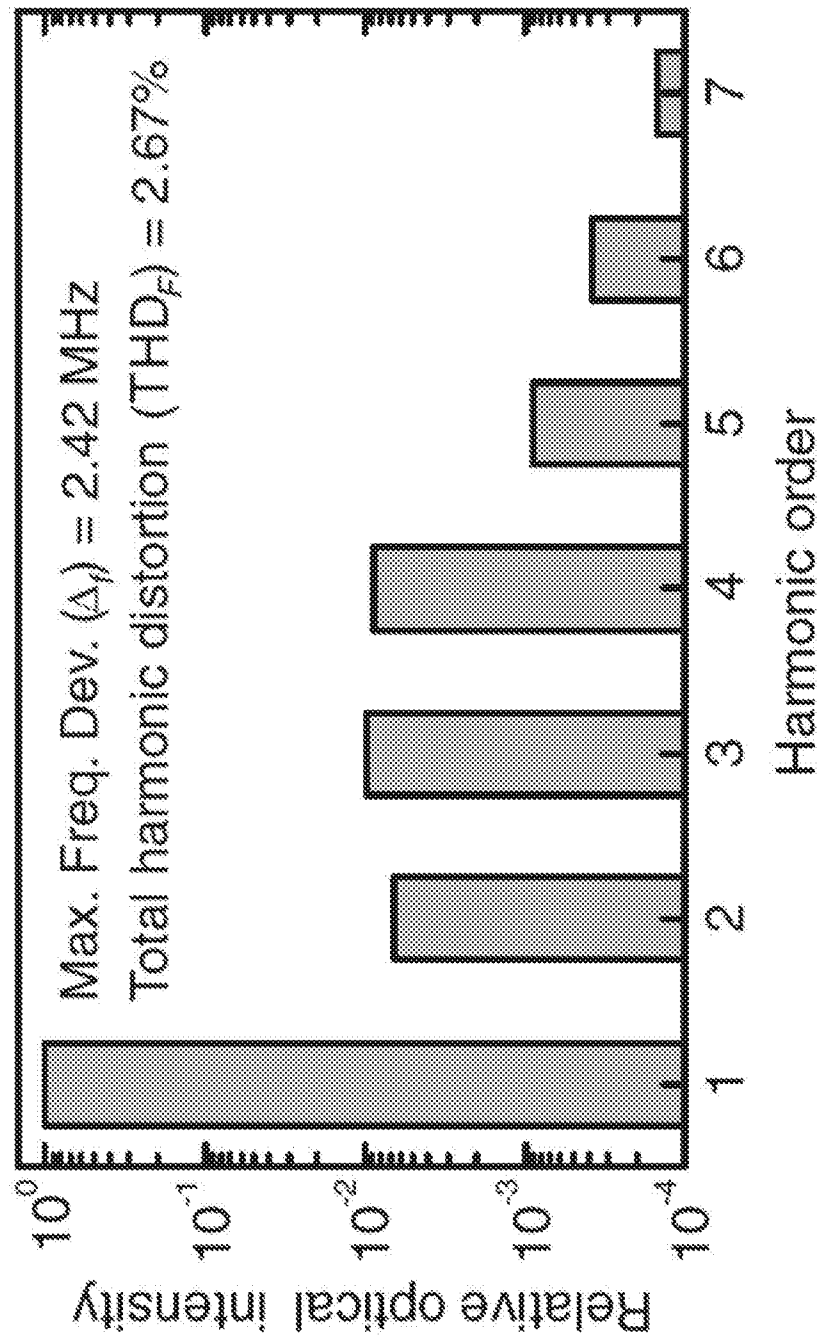


Fig. 17

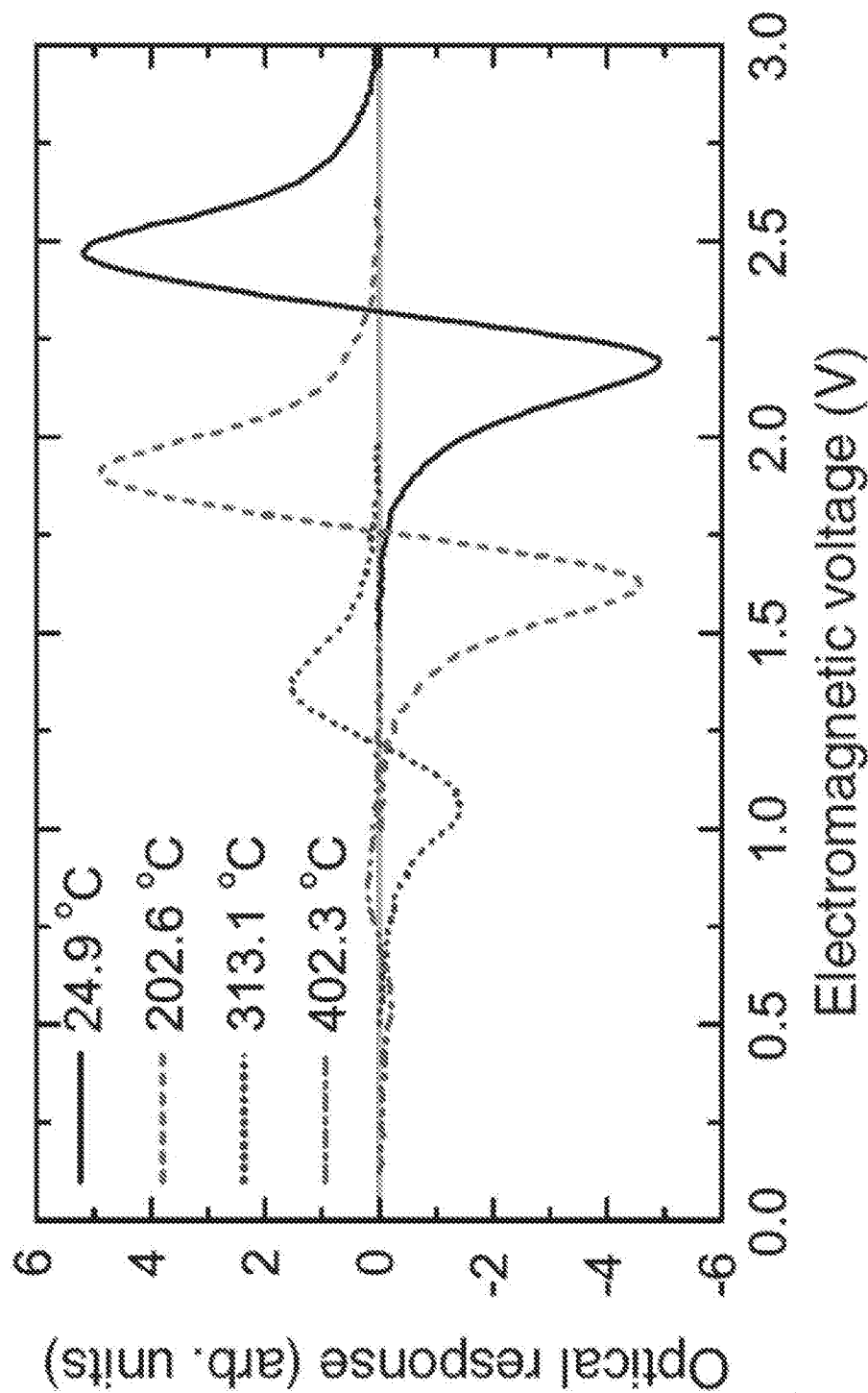


Fig. 18

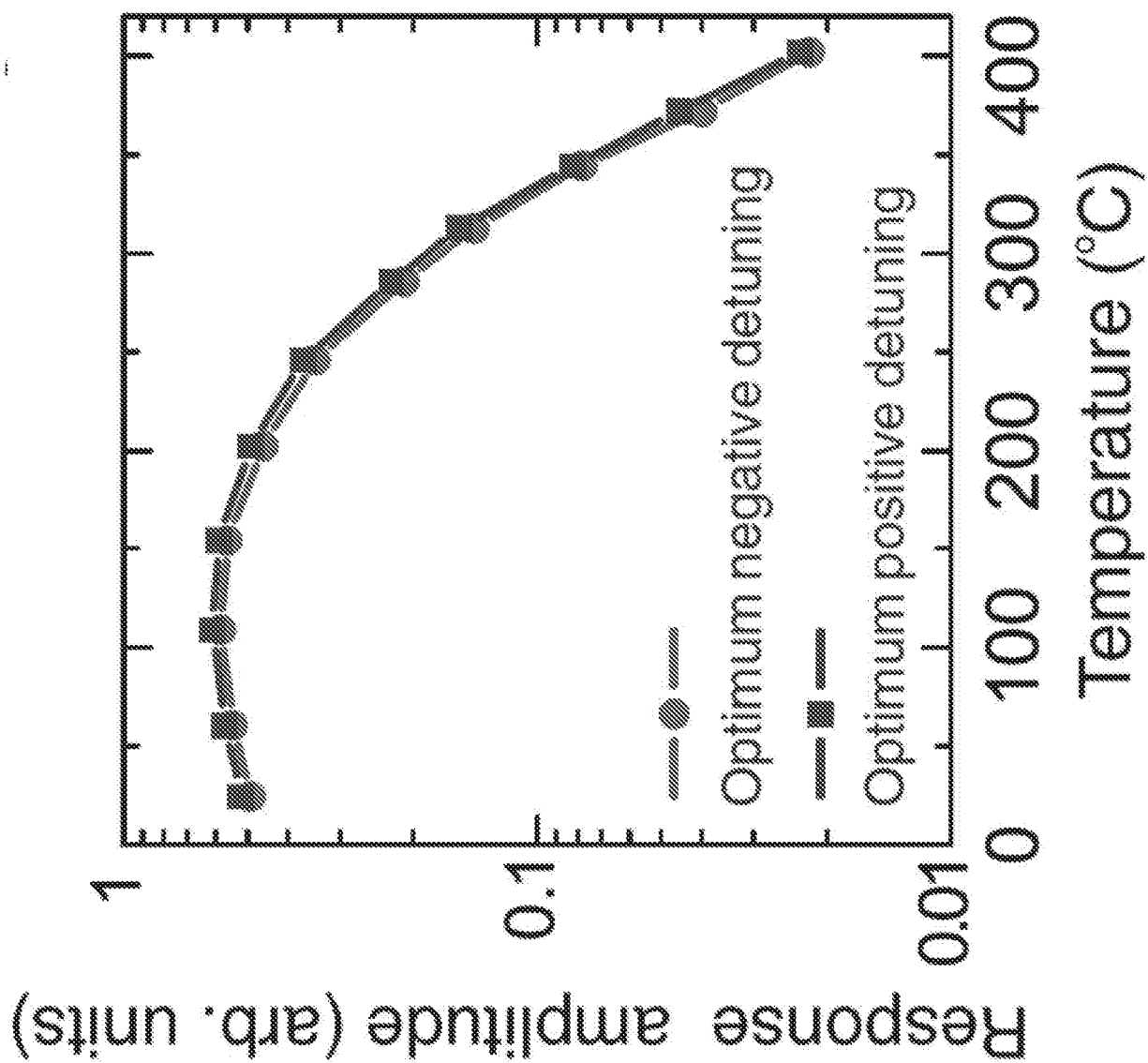


Fig. 19

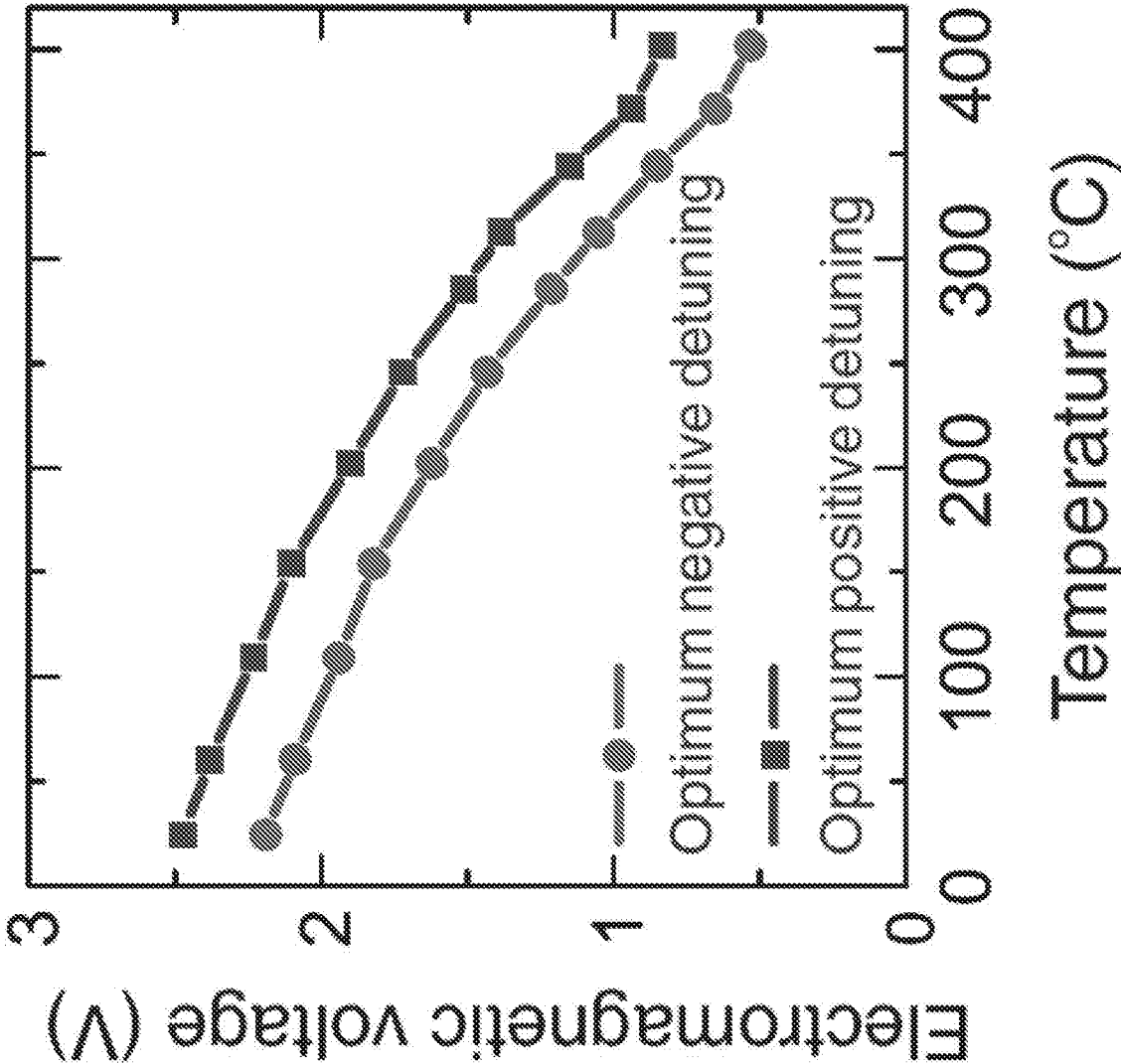


Fig. 20