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(54) **RATE OF PENETRATION/DEPTH MONITOR FOR A BOREHOLE FORMED WITH MILLIMETER-WAVE BEAM**

(71) Applicant: **Massachusetts Institute of Technology**, Cambridge, MA (US)

(72) Inventor: **Paul P. Woskov**, Bedford, MA (US)

(73) Assignee: **Massachusetts Institute of Technology**, Cambridge, MA (US)

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G01S 13/32	(2006.01)

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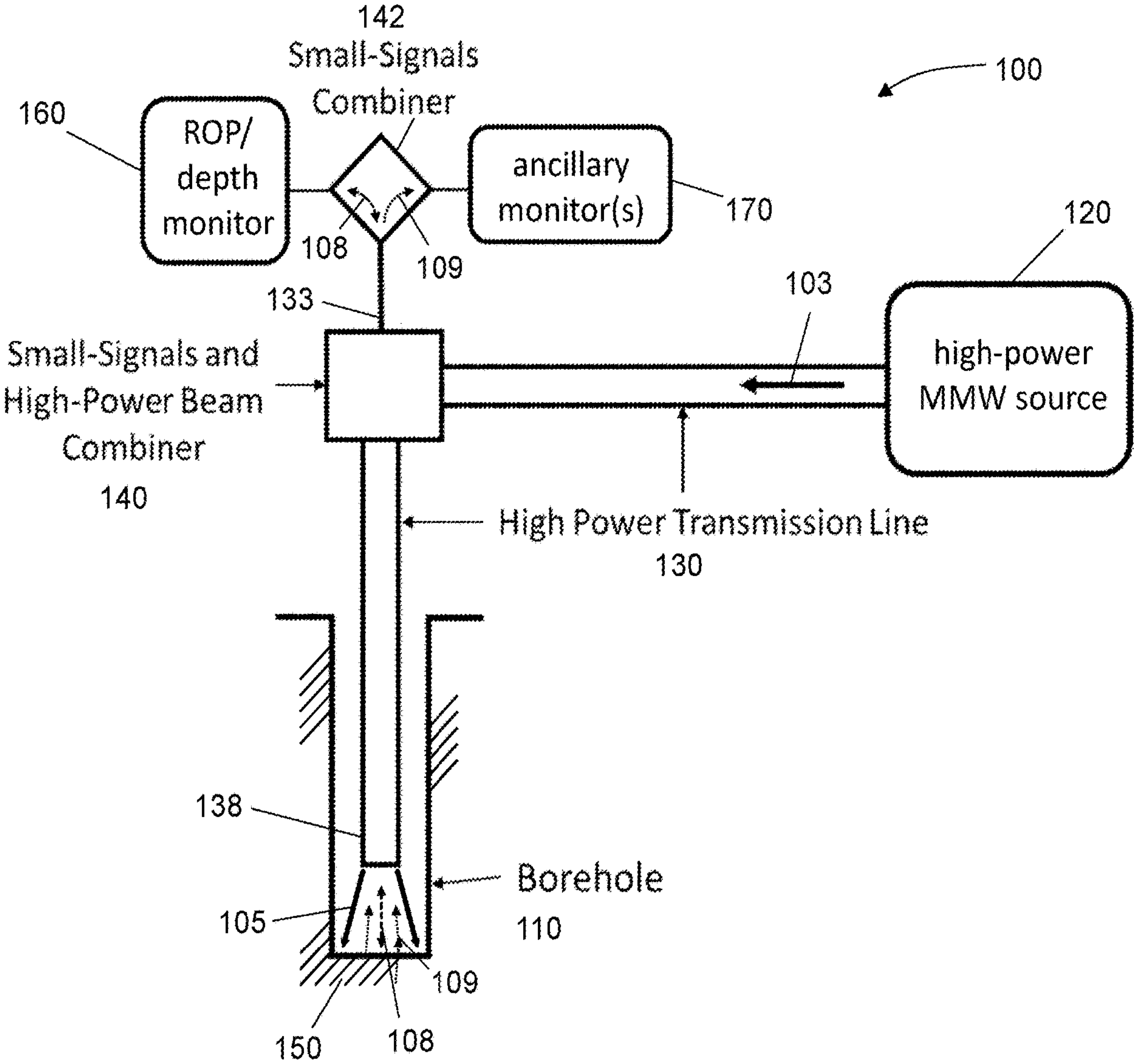
(57) **ABSTRACT**

Apparatus and methods are described for drilling deep boreholes with millimeter-wave radiation in earthen materials to access deep resources such as geothermal heat. Borehole depth and temperature at the bottom of the borehole can be monitored with probe signals and/or radiative emission from the bottom of the borehole.



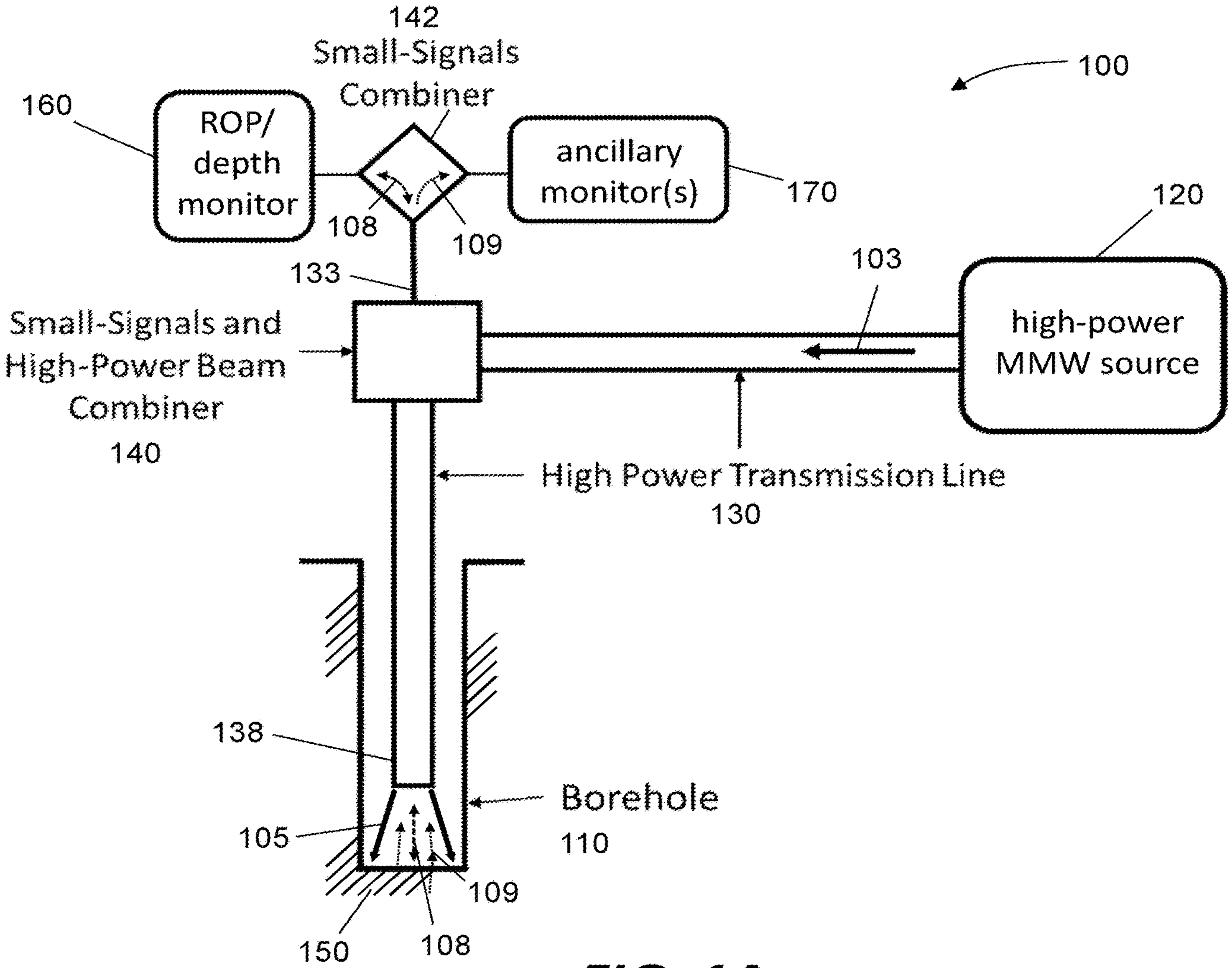

100
142
Small-Signals
Combiner
160
ROP/
depth
monitor
ancillary
monitor(s)
170
108
109
120
133
103
Small-Signals and
High-Power Beam
Combiner
140
high-power
MMW source
High Power Transmission Line
130
138
Borehole
110
105
109
150
108

FIG. 1A

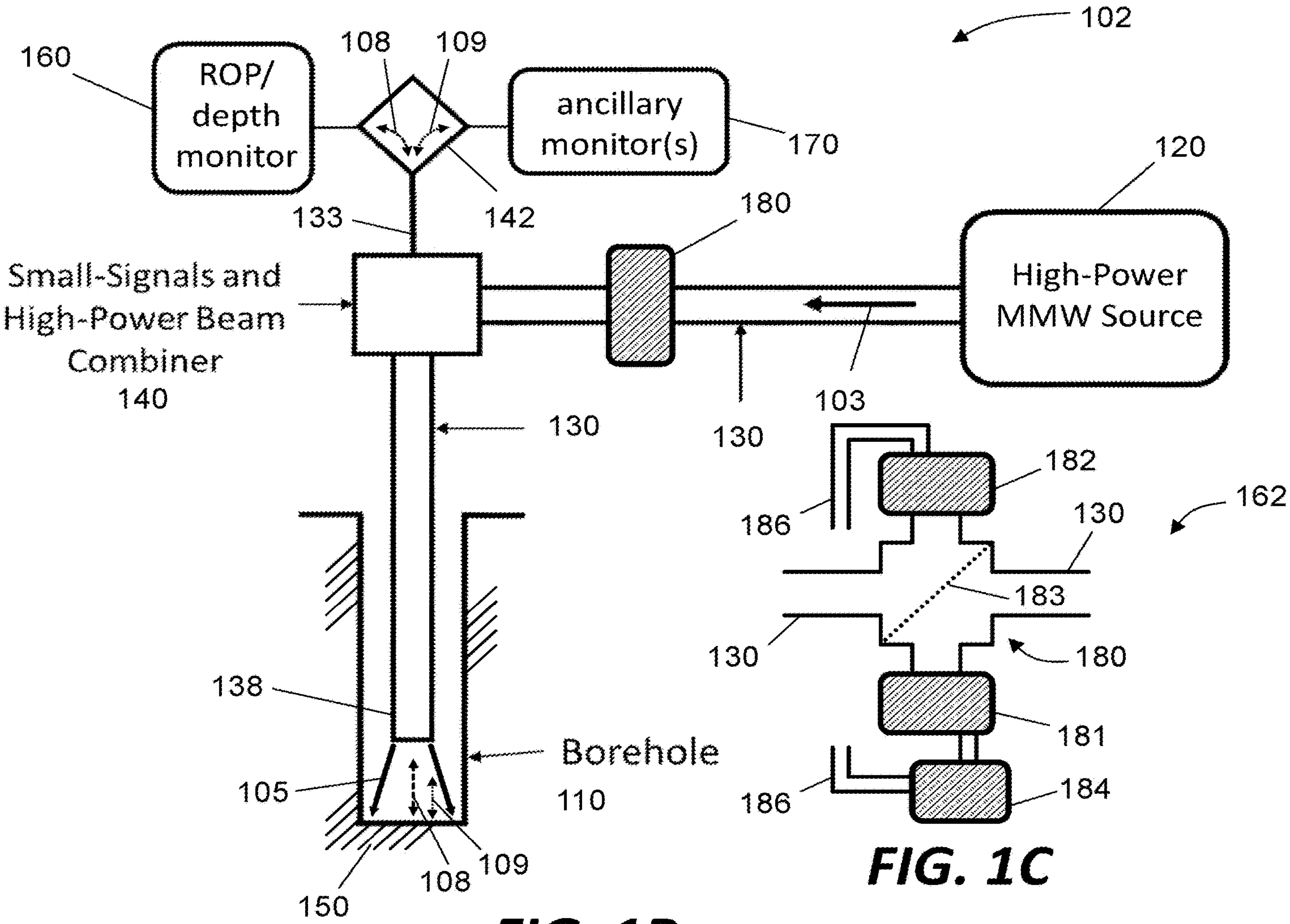

102
160
ROP/ depth monitor
108
109
ancillary monitor(s)
170
142
133
120
180
High-Power MMW Source
Small-Signals and High-Power Beam Combiner
140
103
130
130
138
Borehole
110
105
108
109
150

FIG. 1B

182
162
186
130
183
130
180
181
186
184

FIG. 1C

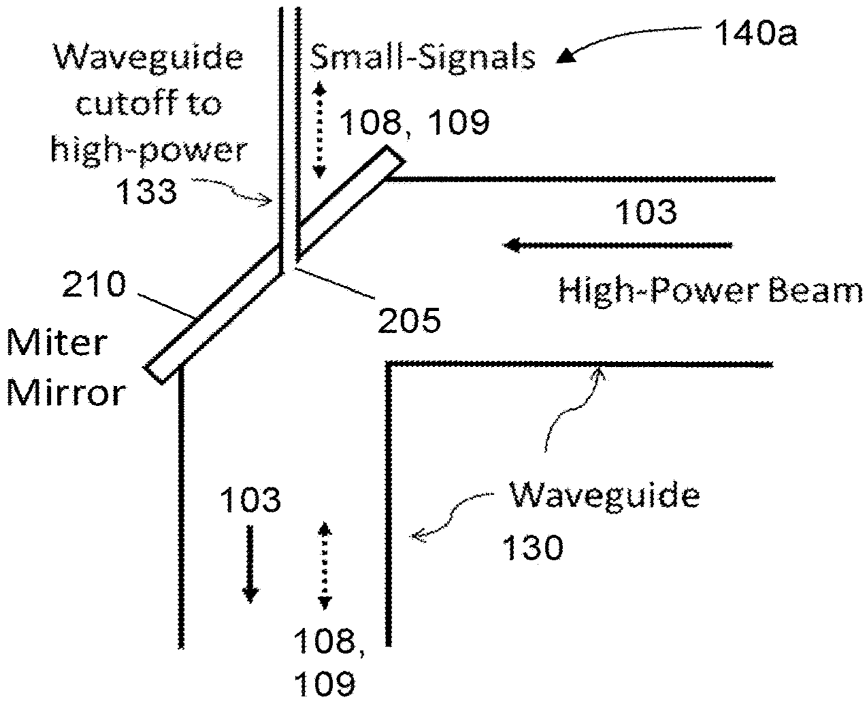

Waveguide
cutoff to
high-power
133
Small-Signals
140a
108, 109
103
High-Power Beam
210
205
Miter
Mirror
103
108,
109
Waveguide
130

FIG. 2A

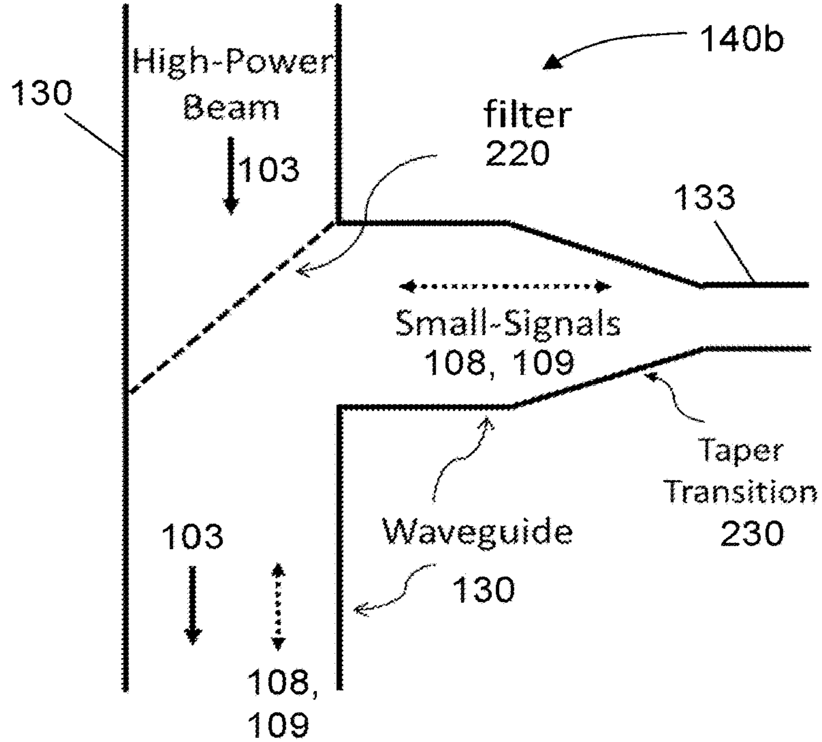
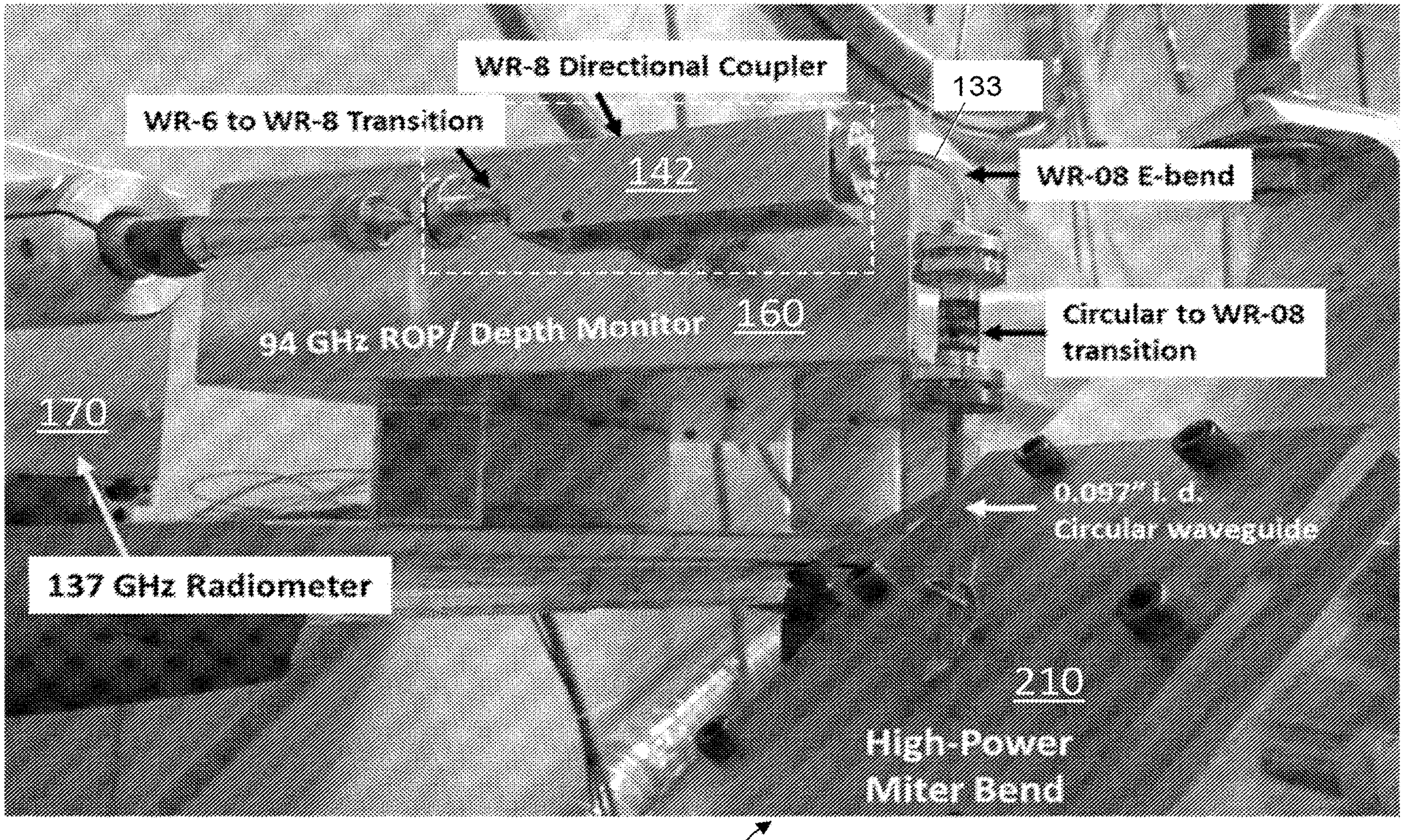

130
High-Power
Beam
103
140b
filter
220
133
Small-Signals
108, 109
Taper
Transition
230
Waveguide
130
103
108,
109

FIG. 2B


WR-8 Directional Coupler
WR-6 to WR-8 Transition
133
142
WR-08 E-bend
94 GHz ROP/ Depth Monitor
160
Circular to WR-08
transition
170
0.097" i. d.
Circular waveguide
137 GHz Radiometer
210
High-Power
Miter Bend

140a

FIG. 3

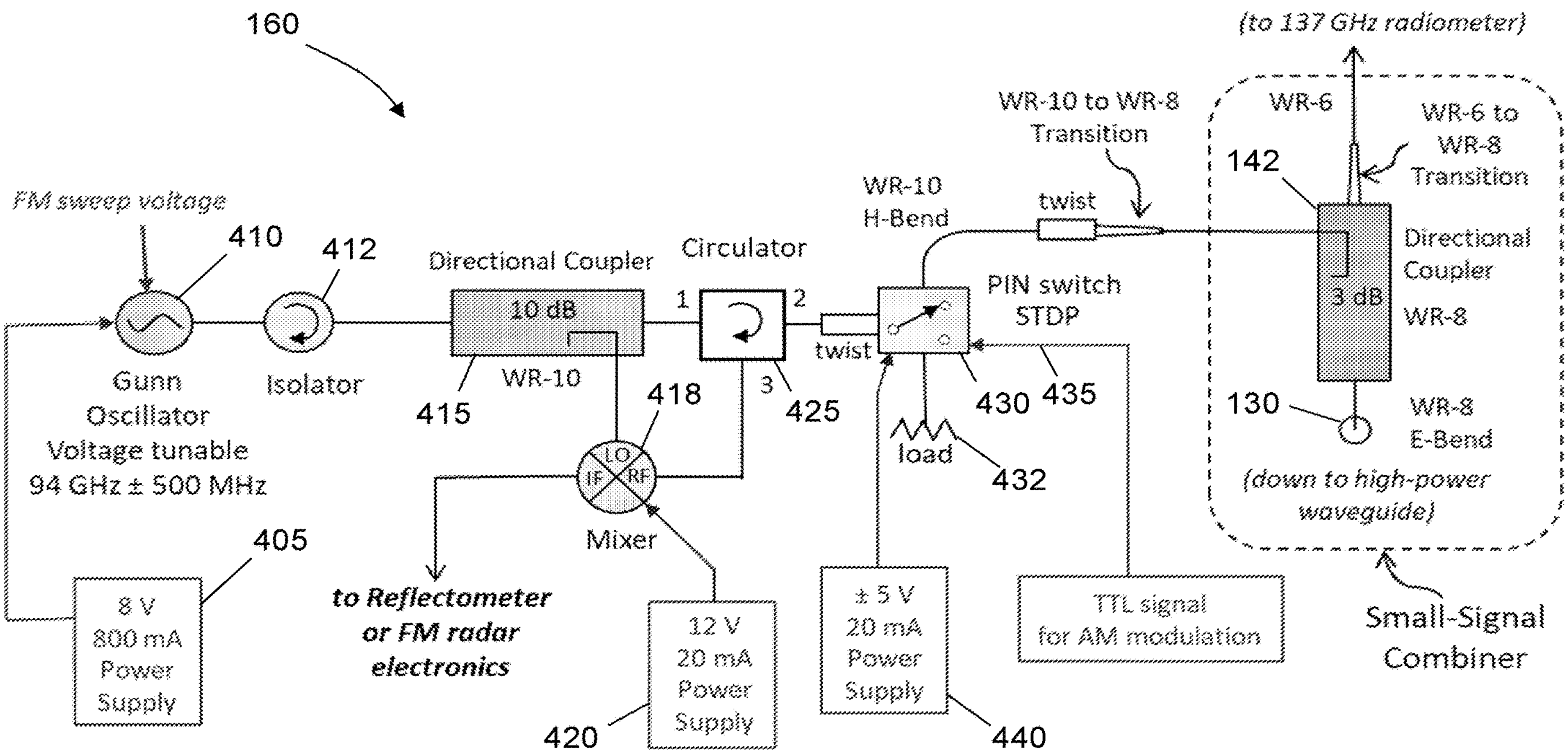

160
(to 137 GHz radiometer)
FM sweep voltage
410
412
Directional Coupler
10 dB
WR-10
415
Circulator
1
2
3
425
Gunn
Oscillator
Voltage tunable
94 GHz ± 500 MHz
Isolator
418
LO
IF
RF
Mixer
405
8 V
800 mA
Power
Supply
to Reflectometer
or FM radar
electronics
12 V
20 mA
Power
Supply
420
WR-10
H-Bend
twist
PIN switch
STDP
430
435
load
432
± 5 V
20 mA
Power
Supply
440
TTL signal
for AM modulation
WR-10 to WR-8
Transition
twist
WR-6
WR-6 to
WR-8
Transition
142
Directional
Coupler
3 dB
WR-8
130
WR-8
E-Bend
(down to high-power
waveguide)
Small-Signal
Combiner

FIG. 4

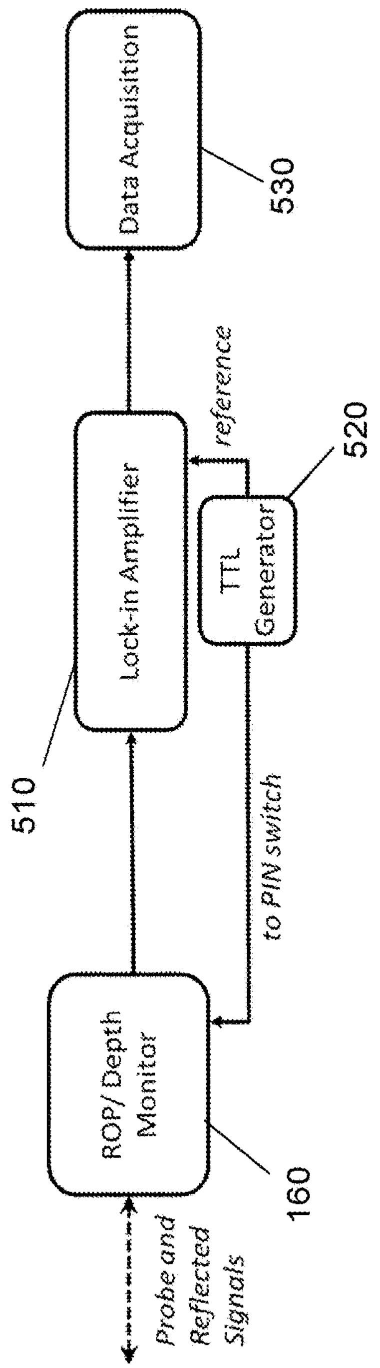

Probe and Reflected Signals
ROP/ Depth Monitor
160
510
Lock-in Amplifier
to PIN switch
TTL Generator
520
reference
Data Acquisition
530

FIG. 5

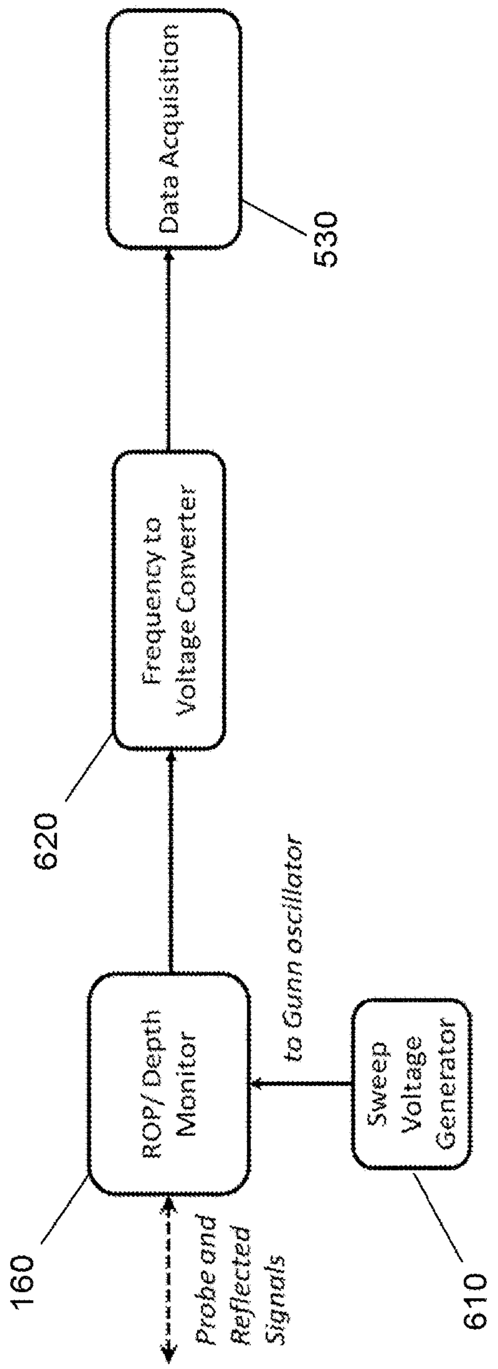
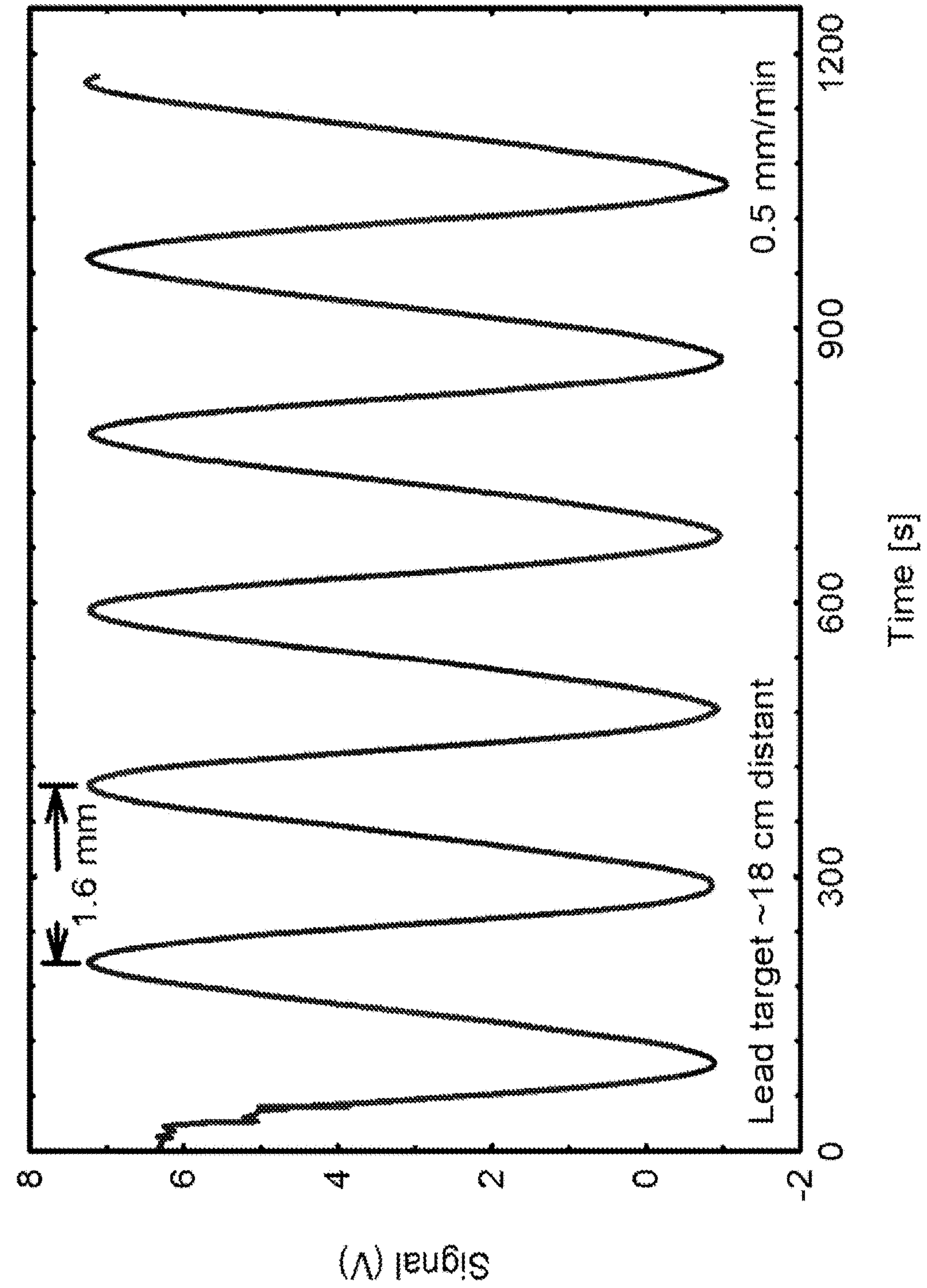

Probe and Reflected Signals
160
ROP/ Depth Monitor
Sweep Voltage Generator
610
to Gunn oscillator
620
Frequency to Voltage Converter
Data Acquisition
530

FIG. 6



Signal (V)
Time [s]
Lead target ~18 cm distant
0.5 mm/min
1.6 mm
8
6
4
2
0
-2
0
300
600
900
1200

FIG. 7

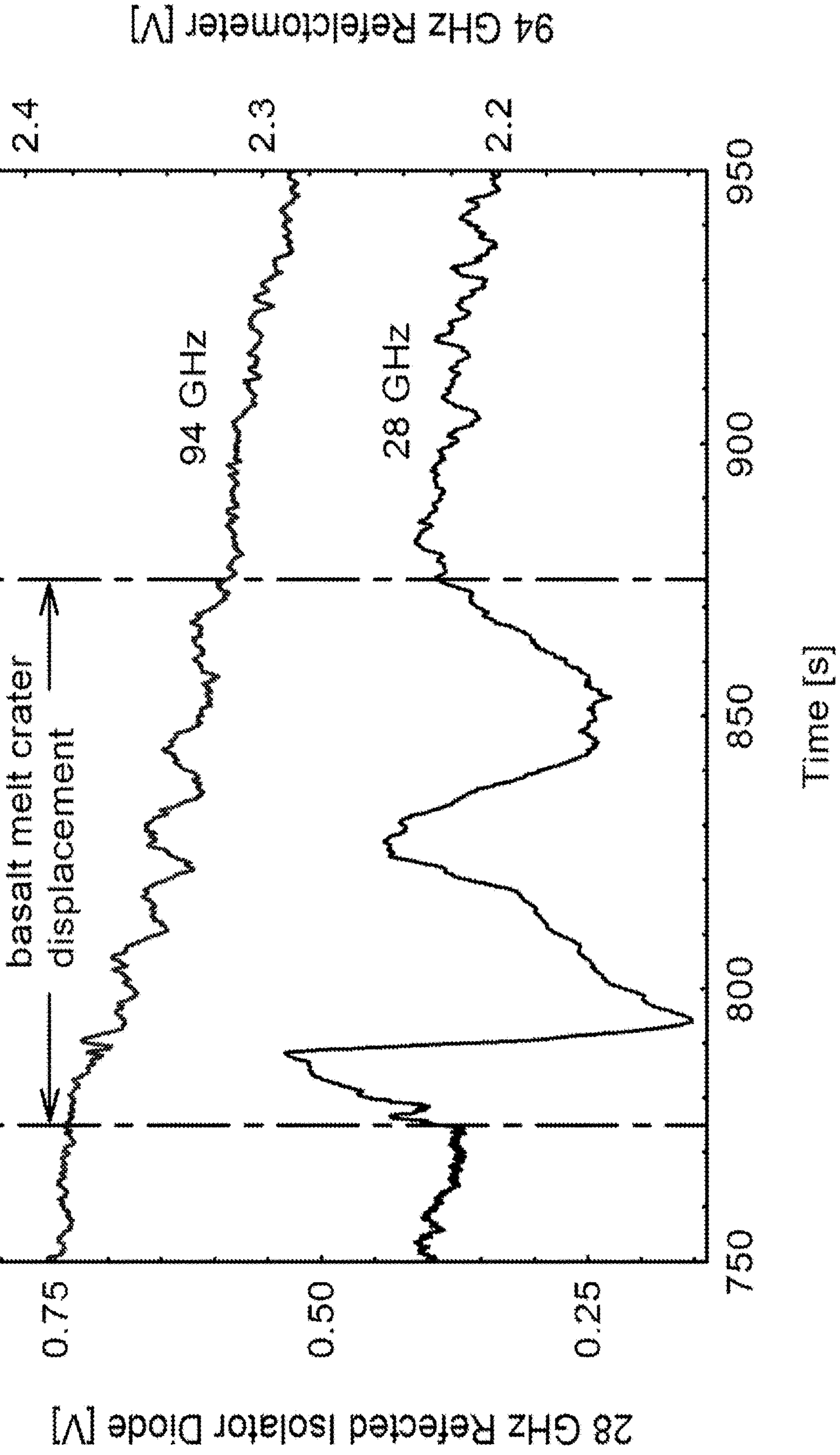

94 GHz Refelctometer [V]
2.4
2.3
2.2
basalt melt crater displacement
94 GHz
28 GHz
0.75
0.50
0.25
750
800
850
900
950
Time [s]
28 GHz Refected Isolator Diode [V]

FIG. 8

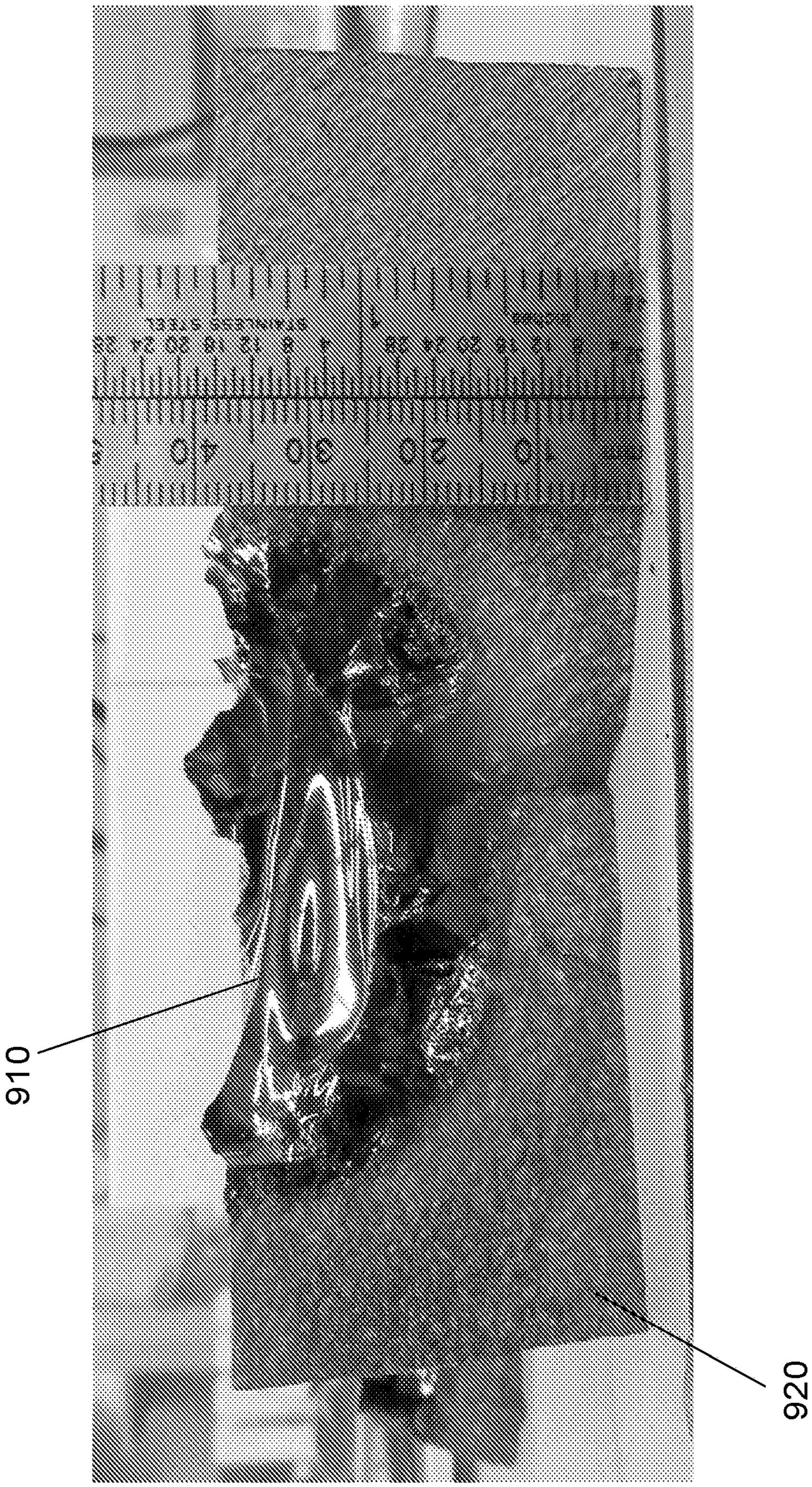


FIG. 9

RATE OF PENETRATION/DEPTH MONITOR FOR A BOREHOLE FORMED WITH MILLIMETER-WAVE BEAM

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application claims a priority benefit, under 35 U.S.C. § 119(e), to U.S. Application No. 63/291,731 filed on Dec. 20, 2021, titled "Rate of Penetration/Depth Monitor for a Millimeter-Wave Beam Made Hole," which application is incorporated herein by reference in its entirety.

GOVERNMENT SUPPORT

[0002] This invention was made with Government support under Grant No. DE-AR0001051 awarded by the Department of Energy. The Government has certain rights in the invention.

BACKGROUND

[0003] A high-power millimeter-wave beam produced by a gyrotron can make a borehole in rock by melting and/or vaporizing the rock. This borehole opening process operates at temperatures greater than the melting and vaporization temperatures of rock of 1000° C. and 3000° C., respectively. Conventional sensors used for monitoring mechanically drilled boreholes require physical contact with the bottom of the borehole and cannot survive at these temperatures.

SUMMARY

[0004] The present technology can be used to form deep boreholes in rock with a high-power millimeter-wave beam and to monitor the bottom of the borehole. The monitoring equipment can remain on the ground surface, at ambient temperature and pressure, regardless of the borehole depth or temperature.

[0005] The present technology includes a method of measuring a depth and/or a rate of penetration of a borehole drilled with a millimeter-wave drilling beam guided by a transmission line to the bottom of the borehole. This method includes coupling a probe signal into the transmission line. The transmission guides the probe signal to the bottom of the borehole, and at least a portion of the probe signal reflects and/or scatters from the bottom of the borehole as a return beam. The transmission line guides the return beam from the bottom of the borehole. The return beam is coupled out of the transmission line and mixed with a local oscillator to produce an intermediate frequency beam whose amplitude and/or frequency are used to determine the depth and/or the rate of penetration of the borehole.

[0006] In some cases, the amplitude of the probe signal is modulated, in which case the depth and/or the rate of penetration of the borehole can be based on the amplitude of the intermediate frequency beam. In other cases, the frequency of the probe signal is modulated, in which case the depth and/or the rate of penetration of the borehole is based on the frequency of the intermediate frequency beam. And in yet other cases, the probe signal comprises a pulse and the depth and/or the rate of penetration of the borehole is based a time of flight of the pulse.

[0007] The probe signal can be generated at a frequency different than a frequency of the millimeter-wave drilling beam or can be picked off from the millimeter-wave drilling beam.

[0008] If desired, a temperature signal at a temperature signal frequency different than the frequency of the millimeter-wave drilling beam (and different than the probe frequency) can be coupled into the transmission line with the probe signal for determining the temperature at the bottom of the borehole.

[0009] Other embodiments of the present technology include a system for drilling a borehole with a source, transmission line, depth/rate-of-penetration monitor, and beam combiner. In operation, the source generates a millimeter-wave drilling beam. The transmission line, which is coupled to the source, guides the millimeter-wave drilling beam to the bottom of the borehole. The depth/rate-of-penetration monitor, which is also coupled to the transmission line, monitors a depth and/or a rate-of-penetration of the borehole. And the beam combiner, which is coupled to the transmission line and the depth/rate-of-penetration monitor, couples a probe signal into the transmission line for transmission to the bottom of the borehole and couples a return beam generated by reflection and/or scattering of the probe signal from the bottom of the borehole from the transmission line to the depth/rate-of-penetration monitor.

[0010] The depth/rate-of-penetration monitor can be configured to operate as a reflectometer, frequency-modulated radar, or pulse-modulated time of flight radar. The depth/rate-of-penetration monitor can generate the probe signal at a frequency different than a frequency of the millimeter-wave drilling beam. In other cases, the beam combiner directs a portion of the millimeter-wave drilling beam returned from the bottom of the borehole to the depth/rate-of-penetration monitor as the return beam.

[0011] The beam combiner may comprise a miter mirror to reflect the millimeter-wave drilling beam around a bend of the transmission line. There can be a hole in the miter mirror to pass radiation at the probe frequency and to reject radiation at the frequency of the millimeter-wave drilling beam.

[0012] The system may also include a temperature monitor to receive a temperature signal for monitoring a temperature of the borehole at a temperature signal frequency different than the frequency of the millimeter-wave drilling beam and different than the probe frequency. And it can include a small-signal beam combiner, coupled to the depth/rate-of-penetration monitor, the temperature monitor, and the beam combiner, to couple the temperature signal with the probe signal.

[0013] All combinations of the foregoing concepts and additional concepts discussed in greater detail below (provided such concepts are not mutually inconsistent) are contemplated as being part of the inventive subject matter disclosed herein. In particular, all combinations of claimed subject matter appearing at the end of this disclosure are contemplated as being part of the inventive subject matter disclosed herein. Terminology explicitly employed herein that also may appear in any disclosure incorporated by reference should be accorded a meaning most consistent with the particular concepts disclosed herein.

BRIEF DESCRIPTION OF DRAWINGS

[0014] The drawings are primarily for illustrative purposes and are not intended to limit the scope of the inventive subject matter. The drawings are not necessarily to scale; in some instances, various aspects of the inventive subject matter disclosed herein may be shown exaggerated or enlarged in the drawings to facilitate an understanding of different features. In the drawings, like reference characters generally refer to like features (e.g., functionally similar and/or structurally similar elements).

[0015] FIG. **1**A illustrates a directed-energy millimeter-wave (MMW) drilling system that uses a high-power drilling beam to drill a borehole and at least one colinear, small-signal probe signal at a different frequency than the high-power drilling beam to monitor the rate of penetration (ROP) and/or depth of the borehole.

[0016] FIG. **1**B illustrates an implementation of a MMW drilling system that uses a high-power drilling beam to drill a borehole and also to monitor the rate of penetration (ROP) and/or depth of the borehole.

[0017] FIG. **1**C depicts details of a ROP/depth monitor that can be implemented with an isolator and detector and can use the MMW radiation used to drill the borehole.

[0018] FIG. **2**A illustrates an implementation of a beam combiner for combining the high-power heating beam with one or more higher-frequency probe signals in the directed-energy MMW drilling system of FIG. **1**A.

[0019] FIG. **2**B illustrates another implementation of a beam combiner for combining the high-power heating beam with one or more lower-frequency probe signals in a directed-energy MMW drilling system like that illustrated in FIG. **1**A.

[0020] FIG. **3** is a photograph of a portion of the MMW drilling system of FIG. **1**A that includes a small-signal combiner that combines a 94 GHz beam for monitoring borehole ROP/depth and a 137 GHz beam for monitoring borehole temperature with a 28 GHz high-power heating beam propagating through a high-power miter bend on a 28 GHz overmoded waveguide (e.g., as shown schematically in FIG. **2**A).

[0021] FIG. **4** illustrates a circuit for generating a 94 GHz probe signal for monitoring borehole ROP/depth using either reflectometry or frequency-modulated (FM) radar techniques. The circuit is shown with an optional small-signal combiner for coupling in a 137 GHz temperature signal.

[0022] FIG. **5** shows a borehole ROP/depth monitor connection with other electronics to operate as a reflectometer.

[0023] FIG. **6** shows a borehole ROP/depth monitor connection with other electronics to operate as an FM radar.

[0024] FIG. **7** is a plot of the signal generated by a 94 GHz ROP/depth monitor beam probing a flat lead target moving uniformly away from the monitor at a starting distance of about 18 cm and a speed of 0.5 mm/min.

[0025] FIG. **8** shows plots of signals generated by a 94 GHz ROP/depth monitor beam (right axis) and by a 28 GHz drilling beam (left axis) both used to probe simultaneously the formation of a melt crater in the surface of a basalt rock while the drilling beam removes the rock.

[0026] FIG. **9** is a photograph of a broken-open cross section of a MMW beam melt crater in a basalt rock.

DETAILED DESCRIPTION

[0027] FIG. **1**A shows a high-power, directed-energy millimeter-wave (MMW) drilling system **100** with at least one monitor **160** for sensing the rate of penetration (ROP) and/or depth of a borehole **110** made by the system in materials **150**, such as earthen material. The system **100** can also include one or more ancillary monitors **170** to monitor one or more conditions at a bottom of the borehole **110**, such as temperature, surface emissivity ε, and melt turbulence among other characteristics. The drilling system **100** uses a high-power MMW drilling beam **105** to "drill" a borehole **110** into the material **150**. The drilling can comprise melting, vaporizing, and/or ablating the material as the borehole deepens.

[0028] High-power MMW radiation **103** from the high-power source **120** can be coupled into high-power transmission lines **130** (which may be implemented as waveguides) and delivered to the bottom of the borehole **110**. At the bottom of the borehole, the high-power MMW radiation **103** can exit the distal end **138** of the transmission line **130** and form the drilling beam **105** that interacts with material in its path. According to some embodiments, the drilling beam **105** has sufficient power to melt granite, for example. A high-power source **120**, such as a gyrotron, can generate the MMW radiation **103** at a frequency in a range from approximately or exactly 30 GHz to approximately or exactly 300 GHz with an average power in a range from approximately or exactly 100,000 Watts to approximately or exactly 2,000,000 Watts. The MMW radiation **103** can be continuous wave at these power levels or can be pulsed to produce higher instantaneous power levels.

[0029] The power and frequency of MMW radiation **103** from the high-power source **120** can be constant with time when the system **100** is drilling the borehole **110**. For example, the power and frequency may remain constant for seconds, minutes, tens of minutes, or even over an hour as the borehole is drilled. In some cases, one or both of the power and frequency of MMW radiation **103** from the high-power source **120** can vary within the frequency range and power range described above when the system **100** is drilling the borehole **110**. For example, the frequency and/or power may change when encountering different materials to improve energy coupling to and heating of the different materials.

[0030] Probe signals **108**, **109** from the monitors **160**, **170** can be radiatively coupled into and from the high-power transmission line **130** with one or more combiners **140**, **142**. The probe signal(s) **108**, **109** can be at one or more different frequencies from a frequency of the high-power drilling beam **105** to sense condition(s) at the bottom of the borehole **110**. Further, the probe signal **108** from the ROP/depth monitor **160** can be at a different frequency than a frequency or frequencies used for the ancillary monitor(s) **170**. For example, the frequency used for the ROP/depth monitor can be in a range from 10 GHz to 300 GHz. In some cases, the frequency used for the ROP/depth monitor can be in a range from 10 GHz to 1 THz. The frequency used for the ancillary monitor(s) can also be in a range from 10 GHz to 300 GHz. In some cases, the frequency used for the ancillary monitor (s) can be in a range from 10 GHz to 1 THz. The power level of probe signals can be in a range from 0.1 Watt to 100 Wats, or even higher power levels in some cases. When detecting thermal emission from the bottom of the borehole **110**, the power level of a received probe signal **109** can be less than 0.1 Watt. The phrase "probe signal" is used herein to refer to a signal that is launched into the borehole by the ROP/depth monitor **160** or an ancillary monitor **170** and used for measuring a characteristic of the borehole **110**. In some cases, an ancillary monitor (such as a temperature radiometer) may not launch a probe signal and instead receive and monitor radiative emissions (e.g., black body radiation) from the borehole. Conditions that can be sensed by the

ROP/depth monitor **160** and ancillary monitor(s) include but are not limited to: the rate of penetration of the borehole **110** as it is being drilled, the depth of the borehole **110**, surface emissivity ε of the earthen material, and a temperature of earthen material **150** as the borehole **110** is being drilled. The depth of the borehole **110** may or may not be measured while the borehole is actively being drilled.

[0031] The high-power transmission line **130** guides the high-power MMW radiation **103** from the high-power source **120** to the bottom of the borehole, where the drilling beam **105** can vaporize rock and other material. The high-power transmission line **130** is typically hollow and of a size that is more than one wavelength in diameter (overmoded) so it can handle high power. It is constructed to reduce or minimize mode conversion so that the most efficient fundamental mode can propagate with minimum losses. There can be some purposeful mode conversion for special applications at launch from the distal end **138** or to negotiate a bend more efficiently, but largely the MMW radiation **103** propagates through the high-power transmission line **130** in a single mode for efficient long-distance transmission. The linearly polarized HE_{11} mode is the most efficient mode in a circular high-power transmission line **130** that is internally corrugated having a good conductor metal surface, such as copper. Other suitable modes include the azimuthally polarized TE_{01} mode in a smooth-walled metal waveguide. This has 69% of the efficiency of the HE_{11} mode in an internally corrugated circular waveguide. The HE_{11} mode can also be guided by the borehole **110**, which acts like a dielectric waveguide, such as a hollow fiber optic cable. For example, the drilling beam **105** can vitrify walls of the borehole **110** as it advances forming a hollow, circular dielectric waveguide.

[0032] The MMW drilling system **100** can include a ROP/depth monitor **160** that is radiatively coupled to the high-power transmission line **130**. The ROP/depth monitor **160** generates a small-signal probe signal, also called a probe signal **108** or probe beam, which can be at a different frequency than the drilling beam **105** for sensing the ROP and/or depth of the borehole. For example, the probe signal **108** may be centered at a probe frequency in a frequency range from 30GHz to 1 THz range with a bandwidth up to 5 GHz. In some cases, the frequency of the probe signal **108** can vary over frequencies within this range of frequencies when making measurements. Preferably, the probe signal **108** can be guided by the same high-power transmission line **130** that guides the drilling beam **105**. The average probe signal power can be in a range from 0.01 Watt to 10 Watts and may be constant or vary over a range of power levels within this range when making a measurement.

[0033] One or more ancillary monitors **170** may generate and/or receive one or more other small-signal probe signals **109** at other frequencies for probing or monitoring other parameters associated with drilling the borehole **110** and the MMW drilling system **100**. In some cases, an ancillary monitor **170** receives radiative emissions from the borehole for analysis. For instance, the ancillary monitor **170** may monitor the borehole temperature by radiometry and/or the waveguide/borehole fill composition by millimeter-wave or terahertz spectroscopy, respectively. In some implementations, the temperature can be monitored by millimeter-wave thermal emission from the bottom of the borehole **110** that couples into the transmission line **130** and propagates back to the ancillary monitor **170**. The radiometer antenna pattern defined by the high-power transmission line **130** and **138** selects the viewed spot size that forms the returned temperature signal. (Thermal emission occurs in all modes, with the receiver antenna pattern selecting the mode(s) that will propagate along the high-power transmission line **130** and be detected by the ancillary monitor **170**. Therefore, the returned thermal signal **109** has properties that are defined at least in part by the radiometer field of view.) In some cases, the fill composition can be monitored by millimeter-wave or terahertz spectroscopic emission or absorption. Spectroscopy performed by an ancillary monitor **170** can be either passive using the thermal blackbody emission background or local plasma excited emission, or active with a frequency-swept probe signal. For passive spectroscopy, the receiving antenna (essentially the high-power transmission line **130**) essentially defines the return signal, as is the case for the return temperature signal. For active probing, the high-power waveguide defines and guides the probe signal. These ancillary probe signals may have average power levels in a range from 0.1 Watt to 100 Watts and may operate at one or more frequencies in a range from 30 GHz to 1 THz.

[0034] In some implementations, temperature monitoring can include launching a temperature probe signal by an ancillary monitor **170** into the borehole **110**. The temperature probe signal can be used to determine surface emissivity ε at the bottom of the borehole. Generally, the radiative emission from the bottom of the borehole (and detected by a temperature radiometer) is the product of surface emissivity and temperature (εT). The emissivity can have a value in a range from 0 to 1. Knowing the surface emissivity can provide a more accurate determination of temperature of earthen material **150** at the bottom of the borehole **110**. Emissivity can be measured by measuring the reflectivity of the surface with the temperature probe signal. For an opaque surface the emissivity can be found from the expression, $\varepsilon=1-r$, where r is the surface reflection.

[0035] Temperature monitoring can be useful for two reasons. First, the temperature of the earthen material can be monitored while drilling to improve removal efficiency. For example, a certain temperature may be maintained while drilling (e.g., using a feedback loop that receives a signal from the drilling area indicative of temperature and adjusts delivered power accordingly). The maintained temperature may be one that vaporizes the earthen material or ablates it into predominantly micro-particles that can be ejected from the borehole using high-pressure gas. The pressurized gas can be pumped down the transmission line **130** and pressurized by energy from the drilling beam **105** which increases the temperature of material in the confined borehole volume as described by the ideal and real gas laws while vapors and/or micro-particles are ejected upward outside the transmission line.

[0036] Second, for geothermal heat access, temperature monitoring is also useful when drilling has ceased, and the earthen material allowed to cool to a lower temperature or its steady-state temperature. In this case, the temperature monitoring can determine when a sufficient depth is reached to access the geothermal heat. For example, the temperature may fall to its steady-state temperature, which can be measured by a temperature monitor. Alternatively, at least one lower temperature can be measured as the temperature falls to its steady-state temperature. A steady-state temperature (at which geothermal energy can be harnessed and further drilling is not needed) can be in a range from 50° C.

to 500° C. An exponential or functional fit to the falling temperature may be used to determine an ultimate steady-state temperature at the bottom of the borehole.

[0037] The ancillary probe signal(s) **109** from the ancillary monitor(s) **170** can be combined with the probe signal **108** from the ROP/depth monitor **160** by a small-signal combiner **142** onto a common small-signal transmission line **133** that carries the probe signals **108**, **109** to and from a power combiner **140**, as depicted in FIG. **1**A. The power combiner **140** couples the combined small-signal probe signals **108**, **109** from the small-signal transmission line **133** to the high-power transmission line **130** that also guides the high-power MMW radiation **103** to the bottom of the borehole **110**. At the bottom of the borehole **110**, the probe signals **108**, **109** can exit and/or enter the distal end **138** of the transmission line **130** to sense physical characteristics (e.g., rate of penetration, temperature, depth of borehole, material composition, melt turbulence, etc.) Black body radiative emissions from the heated earthen material **150** can also enter the distal end **138** of the transmission line **130** for transmission to an ancillary monitor **170**.

[0038] The small-signal probe signals **108**, **109** can return from the bottom of the borehole **110** and can be guided by the high-power transmission line **130** back to the power combiner **140**, which couples the returned small-signal probe signals **108**, **109** to the small-signal combiner **142** via the small-signal transmission line **133**. The small-signal combiner **142** directs the different small-signal probe signals **108**, **109** and/or radiative emissions to the respective monitors **160**, **170**. The return signals can be divided and sent to the respective monitors using frequency, polarization, or time to demultiplex the signals at the small-signal combiner **142**. The monitors **160**, **170** measure the amplitude, frequency, and/or phase of their corresponding received probe signal to derive some information about conditions at the bottom of the borehole **110**, such as the drilling beam's rate of penetration, the borehole depth, surface emissivity, melt turbulence, and/or temperature among other characteristics. Because the monitors **160**, **170** derive information from the returned probe signals **108**, **109** and/or radiative emissions, they can remain on the ground surface, far from the bottom of the borehole **110** which is heated to extreme temperatures. As a result, the monitors do not have to be as rugged as the downhole monitors used to monitor mechanical drills, for example. They can also monitor conditions at the bottom of the borehole **110** that are more extreme (e.g., hotter) than those at bottom of boreholes made with mechanical drills.

[0039] Evaluating melt turbulence can be beneficial for drilling deep boreholes. Melt turbulence can indicate a level of viscosity of the molten earthen material **150**. For some drilling applications, once a suitable viscosity is reached, the molten earthen material **150** can be displaced to the wall of the borehole where it will cool to form a solid casing that lines the borehole **110**. This self-casing can stabilize the borehole **110** and may be sufficiently strong in some cases to prevent collapse of the borehole.

[0040] FIG. **1**B and FIG. **1**C illustrate an alternative high-power, directed-energy MMW drilling system **102**. This system **102** can monitor the rate of penetration and/or depth of the borehole using a portion of the high-power MMW radiation instead of a probe signal **108** at a different frequency. As in FIG. **1**A, a gyrotron or other high-power MMW source **120** generates high-power MMW radiation **103**, which is guided to the bottom of a borehole with a high-power waveguide or transmission line **130**. In this case, however, the rate-of-penetration/depth monitor does not generate and launch a probe signal at a frequency different than the frequency of the high-power MMW radiation **103** that forms the drilling beam **105**. Instead, a beam pick-off by the isolator **180** couples a small portion of the forward high-power MMW radiation **103** via beam dumps **181**, **182** to a gyrotron frequency detector **184** at one of the beam dumps. In addition, the reflected power isolator **180** simultaneously couples a portion of the high-power MMW radiation **103** returned from the bottom of the borehole **110** to the detector **184**. The returned MMW radiation **103** can be coupled through a small-signal transmission line **186** from a reflected power beam dump **182**.

[0041] FIG. **1**C depicts further details of the isolator **180** and detector **184**, which can be part of another implementation of a ROP/depth monitor **162**. More specifically, the reflected power isolator **180** can include a polarizer grill **183** of copper wires at a 45-degree angle to the axis of the high-power transmission line **130**. There can be two beam dumps **181**, **182** opposite each other on each side of the polarizer grill **183**. The MMW radiation **103** is primarily linearly polarized in the HE_{11} mode that passes through the polarizer grill of the power isolator **180** but typically there are unwanted small power components in the wrong polarization that do not pass through the polarizer. The power isolator **180** filters and/or reflects other polarization components of the MMW radiation **103** out to the side beam dumps **181**, **182** depending on the direction of travel of the MMW radiation **103**. One forward beam dump **181** can absorb the filtered forward power and the second reflected power beam dump **182** can absorb the return reflected power. In some cases, the beam dumps **181**, **182** are not perfect and can cross scatter power to each other. In such cases, a small-signal waveguide **186** may not be needed. The polarizer grill **183** reflects power returned from the target at the bottom of the borehole **110** into the reflected power beam dump **182**. This returned and reflected power has its polarization flipped 90 degrees by a circular polarizing mirror in the miter bend that would be part of the small-signals and high-power beam combiner **140** as shown in FIG. **2**A. A circular polarizing mirror has grooves in its surface that circularly polarize an incident linearly polarized beam and re-polarizes a return refection to an orthogonal linear polarization to the incident beam. The detector **184** (e.g., a 28 GHz diode) located off center on the forward beam dump **81** picks up these signals rejected by the polarizer grill. The forward and returned signal components coherently interfere in the diode detector to produce a detected signal amplitude that depends on the relative phase of the forward and reflected signals that in turn depends on the distance to the rock melt surface. The isolator **180** and detector **184** can be used to implement a second ROP/depth monitor **162** that can be used alone or in addition to the ROP/depth monitor **160** (which can operate at a different frequency) to improve distance measurement reliability and accuracy.

[0042] In the second ROP/depth monitor **162**, the reflected signal from the polarizing grill mixes coherently with the portion of the forward-traveling high-power MMW radiation **103** coupled to the ROP/depth monitor **162** for use as a local oscillator. The ROP/depth monitor **160** can have its own frequency source that provides the local oscillator signal for that monitor, which can be at a frequency different than the frequency of the MMW radiation **103**. The ROP/

depth monitors **160**, **162** detect their beat or intermediate frequency caused by mixing their respective local oscillator signals with received reflected signals from the borehole **110** and they process their respective detected beat signals to determine ROP or depth of the borehole **110**. If the MMW radiation **103** and drilling beam **105** are at a constant frequency, the rate-of-penetration/depth monitor **162** acts a reflectometer, with the number of amplitude maxima and minima representing the depth of the borehole as described below. If the frequency of the MMW radiation **103** and drilling beam **105** are chirped or swept, the rate-of-penetration/depth monitor **162** acts as a frequency-modulated (FM) radar, with the phase or frequency of the beat representing the depth of the borehole as described below. Similarly, the frequency source of the ROP/depth monitor **160** can be fixed or swept to operate the ROP/depth monitor as a reflectometer or FM radar, respectively.

1. Combining Frequency-Multiplexed Probe Signals with Guided High-Power MMW Radiation

[0043] In some examples, the high-power MMW radiation **103**, small-signal probe signals **108**, **109**, and radiative emissions of interest from the bottom of the borehole **110** are at different frequencies so that they can be frequency multiplexed and demultiplexed using the small-signal combiner **142** and power combiner **140**. The small-signal monitors **160**, **170** can be radiatively coupled to the high-power transmission line **130***b* by using fundamental mode microwave/millimeter-wave waveguide components, such as signal dividers, directional couplers, or frequency multiplexers. (A waveguide that supports only a fundamental mode has a cross section less than one wavelength or on the order of one-half wavelength of the radiation used by a small-signal monitor **160** or **170**.) The monitors' probe signals **108**, **109** can be coupled to the high-power transmission line **130** using configurations described in connection with FIG. **2**A and FIG. **2**B. The high-power transmission line **130** can be overmoded for the probe signals (e.g., a waveguide diameter used for the transmission line **130** can be much larger than the wavelength of radiation used for the probe signals **108**, **109**).

[0044] FIG. **2**A and FIG. **2**B depict examples of power combiners **140***a*, **140***b* that can radiatively couple the small-signal probe signals **108**, **109** propagating to and from the monitors **160**, **170** onto and from the high-power transmission line **130** that carries the high-power MMW radiation **103** to the bottom of the borehole **110**. The configuration of the power combiner depends on the relative frequencies of the small-signal probe signals **108**, **109**, radiative emissions of interest, and the high-power MMW radiation **103**. The power combiner **140***a* in FIG. **2**A can combine a small-signal probe signal at higher frequency with a lower frequency high-power MMW radiation **103** traveling along the transmission lines **130**. The power combiner **140***b* in FIG. **2**B can combine a small-signal probe signal **108** and/or probe signal **109** at lower frequency with a higher frequency high-power drilling beam.

[0045] In the beam combiner of FIG. **2**A, a small coupling hole **205** in a miter mirror **210** that is mounted at a bend in the high-power transmission line **130** can be used to couple in the higher-frequency probe signal(s) **108**, **109** with the lower-frequency MMW radiation **103** without perturbing the drilling beam **105**. The high-power MMW radiation **103** reflects off the miter mirror **210**, e.g., downward toward the bottom of the borehole **110** as in FIG. **1**A. At the same time, the small-signal probe signals **108**, **109** from the monitors **160**, **170** propagate through the coupling hole **205** in the miter mirror **210** and downward to the bottom of the borehole. The returned small-signal probe signals **108**, **109** and/or radiative emissions pass upward through the hole **205** in the miter mirror **210** to the monitors **160**, **170**. The diameter of the coupling hole **205** and/or inside diameter of the small-signal transmission line **133** are less than one half wavelength of the high-power MMW radiation **103** to prevent the MMW radiation **103** from propagating toward the monitors **160**, **170**. In other words, the coupling hole **205** in the miter mirror **210** and/or small-signal transmission line **133** allow only evanescent propagation of the MMW radiation **103** toward the monitors **160**, **170** and effectively act(s) as a low-frequency cutoff or high-pass filter. Mode conversion loss in the coupling between the small-signal transmission line **133** and the high-power transmission line **130** can be calibrated out.

[0046] In the power combiner **140***b* of FIG. **2**B, a dichroic or polarization-dependent filter **220** in the high-power transmission line **130** passes the higher frequency high-power MMW radiation **103** and reflects the lower frequency small-signal probe signals **108**, **109** and/or radiative emissions from the bottom of the borehole **110**. More specifically, a polarization-dependent filter **220** could be implemented as a wire grill or mesh with a low density of wires. For example, a wire grill (comprising straight, parallel conductive wires or conductive traces) can transmit a first, linearly polarized wave and reflect a second linearly polarized wave having its polarization oriented orthogonal to the first polarized wave. As another example, a dielectric window mounted at an appropriate angle or thickness can be used as a frequency-selective filter **220** to separate radiation at two different frequencies. The filter **220** is configured to transmit the high-power MMW radiation **103** downward toward the bottom of the borehole **110**. The dichroic or polarization-dependent filter **220** also reflects the probe signals **108**, **109** from the monitors **160**, **170** downward toward the bottom of the borehole **110** via the high-power transmission line **130** and reflects the returned probe signals **108**, **109** and/or radiative emissions of interest toward the monitors **160**, **170** via the small-signal transmission line **133**.

[0047] A transition region comprising a section of tapered waveguide **230** can be located between the small-signal transmission line **133** and the high-power transmission line **130** and may be located near the dichroic or polarization-dependent filter **220** (e.g., within 10 cm of the mirror). The tapered waveguide **230** can transform the transverse mode from the small-signal transmission line **133** to better match to a mode supported by the high-power transmission line **130** and vice versa so as to reduce mode coupling losses between the two transmission lines. In some cases, even though the wavelength(s) of the probe signal(s) can be longer than the wavelengths of the high-power MMW radiation **103**, the diameter of the small-signal transmission line **133** can be much smaller than the diameter of the high-power transmission line **130**. The tapered waveguide **230** aides in coupling the probe signals **108**, **109**, which propagate in the small-signal transmission line **133**, to and from the larger high-power transmission line **130**. The taper of the tapered waveguide **230** can be linear or parabolic and should be long enough to reduce or minimize mode conversion losses (e.g., below 10 dB). Parabolic tapers are generally shorter than linear tapers. The internal surface of the tapered waveguide **230** preferably matches the internal surfaces of the transmission lines to which the tapered waveguide **230** connects. For example, the tapered waveguide **230** may have a corrugated internal surface to transmit the HE_{11} mode efficiently when the transmission lines **130**, **133** to which it connects are implemented as waveguides having corrugated internal surfaces. The end widths (diameters) of the tapered waveguide **230** are sized to match the widths (diameters) of the transmission lines to which the ends connect. A high-power gyrotron frequency notch filter may also be added to the small signal monitoring waveguide to further reject any stray or scattered high-power gyrotron electromagnetic radiation.

[0048] One example of a high-power dielectric component that can be used in a power combiner **140*b*** is a diamond plate oriented at Brewster's angle, which is 67 degrees for diamond in air at one atmosphere pressure. The diamond plate combines and separates beams with orthogonal linear polarizations. At Brewster's angle, the polarization in the plane-of-incidence (plane containing the incident and reflected beam vectors and the normal to the plate) is transmitted with no loss (except for very minor plate absorption) and the beam with perpendicular polarization to the plane-of-incidence is highly reflected. The transmitted beam would be the high-power MMW radiation **103** propagating along the high-power transmission line **130** and the reflected beam would be the probe signal **108** and/or probe signal **109**.

[0049] FIG. **3** is a photograph of a portion of a directed-energy MMW drilling system and shows a small-signal beam combiner **142** coupled to a power combiner **140*a*** like the power combiner shown in FIG. **2**A. The small-signal beam combiner **142** decouples a 135-139 GHz radiative emission or temperature signal **109** received from the borehole **110** for temperature radiometry and a 94 GHz ROP/depth returned probe signal **108** from a small-signal transmission line **133** (implemented as a rectangular waveguide, a circular to rectangular transition, and a circular waveguide) that bends 90 degrees toward a high-power miter mirror **210**. A temperature radiometer is used as the ancillary monitor **170**. A hole in the miter mirror **210** radiatively couples the collinear, combined returned probe signal **108** and temperature signal from a larger diameter, high-power transmission line (not visible in the photograph) below the miter mirror **210** to the monitors **160**, **170**, such that the probe signal **108** and temperature signal propagate along the high-power transmission line with 28 GHz high-power radiation that is used to form the drilling beam **105**. The top of the copper miter mirror **210**, which is mounted on a 3" (76 mm) internal diameter 28 GHz high-power transmission line, is shown in the lower right of FIG. **3**. The small-signal transmission line **133** comprises a 0.097" (2.5 mm) internal diameter copper circular waveguide having a vertical portion attached to the miter mirror **210** and aligned to a hole of the same diameter in the center of miter mirror, which introduces the probe signal **108** into the high-power transmission line to propagate colinearly with the high-power MMW radiation.

[0050] Continuing up from the miter mirror **210** in the example system of FIG. **3**, a circular-to-rectangular waveguide transition to wr-8 band (90-140 GHz) is attached followed by a wr-8 E-plane bend. The E-plane bend attaches to a 3 dB wr-8 directional coupler orientated horizontally, which splits the combined return probe signal **108** and temperature signal between the two monitors **160**, **170**. The returned probe signal **108** for the 94 GHz ROP/depth monitor **160** and the temperature signal **109** for the GHz temperature radiometer are separated by the directional coupler in combination with a wr-8 to wr-6 (110-170 GHz) waveguide transition to the ancillary monitor **170** and a wr-8 to wr-10 (75-110 GHz) transition (partly visible) to the ROP/depth monitor **160**. The wr-6 to wr-8 waveguide transition prevent the ROP/depth probe signals from interfering with the radiometer's received temperature signals because 94 GHz cannot propagate in the wr-6 waveguide. Likewise, the 28 GHz high-power drilling beam cannot propagate in the 0.097" diameter waveguide, shielding the monitors while giving them full access to monitoring the borehole target surface with higher-frequency beams.

2. Rate of Penetration/Depth Monitor Instrument

[0051] The ROP/depth monitor **160** can operate as either a reflectometer (reflection interferometer), a frequency-modulated (FM) radar, or a pulsed time-of-flight radar. In the reflectometer configuration, the frequency of the small-signal ROP/depth probe signal **108**, also called the probe frequency, is fixed. The returned probe signal **108** is mixed with an un-transmitted part of itself to produce a DC signal whose amplitude depends on the round-trip return phase of the returned probe signal **108** relative to what it was before transmission. For a change in depth equal to a quarter of a wavelength at the probe frequency, the detected signal amplitude should vary from a maximum to a minimum or vice versa. Put differently, in the reflectometer configuration, the ROP/depth monitor **160** has a depth resolution, Δz, that can be written as:

$$\Delta z = \frac{1}{4}\lambda, \quad (1)$$

where λ is the wavelength at the probe frequency. The ROP is determined by measuring the rate at which the signal changes from maximum to minimum and the depth is determined by counting the number maximum-to-minimum changes from a starting or reference phase of the probe transmission as a function of time.

[0052] In the FM radar configuration, the probe frequency is swept over a bandwidth of Δf at some modulation frequency rate f_m. The phase shift of the round-trip reflection when detected in a mixer with an un-transmitted copy of the ROP/depth probe signal **108** generates a tone at an intermediate beat frequency, f_B, that is proportional to the depth, Z. The depth is given by:

$$Z = \frac{cf_B}{4f_m\Delta f}, \quad (2)$$

where c is the speed of the MMW propagation in the high-pressure fill of the high-power MMW transmission line **130**. In some implementations, a gas may be forced down the transmission line **130** to aid in removal of vaporized and/or particulate material from the bottom of the borehole **110** to deepen the borehole. The resolution of the depth depends on the bandwidth of the frequency sweep:

$$\Delta z = \frac{c}{2\Delta f}. \quad (3)$$

[0053] The relative merits of the reflectometer and FM radar configurations can be appreciated by considering an example frequency. At 94 GHz (λ=3.19 mm) and tuning bandwidth of 1 GHz typically available for a commercial Gunn oscillator, the depth resolution for the reflectometer would be 0.8 mm (Eq. 1) and 150 mm for the FM radar (Eq. 3). The reflectometer is better suited for shallow boreholes (e.g., laboratory boreholes) that are less than a few times deeper than the FM radar resolution, while the FM radar is better suited for deep boreholes in the field. Also, the measurement of a frequency is more reliable for a deep borehole than an amplitude change that could vary for reasons other than a phase change.

[0054] In the time-of-flight configuration, a short electromagnetic pulse (having a full-width-half-maximum pulse duration of τ) is transmitted toward the bottom of the borehole. The round-trip time delay for the pulse's return to the surface electronics can be used to determines the distance to the bottom of the hole. The relation is given by:

$$Z = c\Delta t/2 \quad (4)$$

where c is the speed of the transmitted pulse and Δt is the round-trip delay time. The spatial resolution depends on the pulse length, τ, and the speed of the transmitted pulse:

$$\Delta z = c\tau \quad (5)$$

In air at atmospheric pressure, the speed of propagation is the speed of light. For a 1 ns pulse, which corresponds to available 1 GHz electronics, the resolution would be 300 mm.

[0055] The peak pulse power level could be as high at 100 kW in pulsed operation. The high-power and lower spatial resolution with a time-of-flight configuration would be suitable for the deepest boreholes that are drilled.

[0056] FIG. **4** shows details of circuitry for a 94 GHz ROP/depth monitor **160** that can operate as a reflectometer or as an FM radar. The circuitry is built with wr-10 waveguide components used for the 75-110 GHz band. A voltage-tuned, 94 GHz±0.5 GHz Gunn oscillator **410** is driven by an 8 V, 800 mA power supply **405** and is connected to a 10 dB directional coupler **415** through an isolator **412** that protects the Gunn oscillator from back reflections. The directional coupler directs 10% of the Gunn oscillator output to a biased mixer **418**, which is powered by 12 V, 20 mA power supply **420**, as a local oscillator for determining the depth. The directional coupler directs the remaining 90% of the Gunn oscillator output to a three-port circulator **425** as the small-signal ROP/depth probe signal. The three-port circulator **425** directs this probe signal from port **1** to port **2**, which is coupled to a solid-state single-pole double-throw (SPDT) PIN switch **430** powered by a ±5 V, 20 mA power supply **440** and controlled by a transistor-transistor logic (TTL) signal provided on a control input **435**. The PIN switch **430** has one output connected to a load **432** and another output connects via waveguide components to a small-single combiner **142** as shown in FIG. **3** and described above. The small-signal combiner **142** combines the 94 GHz ROP/depth probe signal to a high-power transmission line **130** leading down the borehole. The small-signal combiner **142** can further direct a radiometry signal from the borehole and high-power transmission line **130** to a temperature radiometer for temperature monitoring. The combiner **142** also directs the returned probe signal from the borehole to port **2** of the three-port circulator **425**, which outputs the returned probe signal to the biased mixer **418** via port **3** for detection. The returned signal from the biased mixer can then go to reflectometer or FM radar electronics for processing and determining depth of the borehole.

[0057] The circuitry of FIG. **4** can be operated as an FM radar when a frequency sweep voltage is applied to the Gunn oscillator and the PIN switch is set to continuously transmit and receive a signal. The PIN switch **430** can also be removed from the circuit to reduce transmit and signal loses due to absorption in the switch. FIG. **5** shows the ROP/depth monitor **160** connected to a lock-in amplifier **510**, TTL signal generator **520**, and data acquisition electronics **530** for operation as a reflectometer. The TTL generator provides a 5 V square wave at a frequency typically over 100 Hz to the PIN switch's control input **435** (FIG. **4**) to alternately direct the probe signal to the target or to the load **432**, which modulates the probe signal from the ROP/depth monitor **160** sent down the borehole. The returned amplitude-modulated (AM; on/off) reflectometer signal is acquired by the lock-in amplifier **510** using a signal from the TTL generator **520** as a reference. Using the lock-in amplifier **510** allows detection of very weak signals. The output of the lock-in amplifier **510** is directed to a data acquisition system that can process, store, and/or display signals from the lock-in amplifier.

[0058] FIG. **6** shows the ROP/depth monitor **160** connected to a voltage sweep generator **610**, frequency-to-voltage converter **620**, and data acquisition electronics **530** for operation as an FM radar. Output from the sweep voltage generator **610** is applied to the Gunn oscillator **410** (FIG. **4**) to modulate the probe frequency (e.g., it linearly sweeps or chirps the frequency of the probe signal). The biased mixer **418** mixes the resulting returned probe signal with a local oscillator copy of the un-transmitted swept-frequency probe signal to generate a tone at the intermediate frequency (IF) port of the mixer whose beat frequency is proportional to the distance to the target (bottom of borehole). This beat frequency can be acquired by the data acquisition electronics **530** directly for further processing or can be converted to a voltage by the frequency-to-voltage converter **620** and provided to the data acquisition electronics **530**. Received data can be processed, displayed, and/or stored by the data acquisition electronics **530**. When the ROP/depth monitor is configured for FM radar operation, the PIN switch **430** is maintained in a position to continuously transmit and receive the signals (e.g., no switching signals to the load **432**). In some implementations, the PIN switch **430** can be removed from the circuit to increase signals strength.

[0059] FIG. **7** shows an example of the signal detected by the ROP/depth monitor **160** when operated as reflectometer. The target in this case was a flat lead brick on a motorized translation stage located about 18 cm from a launch horn connected to a wr-10 waveguide output of the reflectometer (e.g., an output from the PIN switch **430**), which would normally be coupled to the small-signal combiner **142** as shown in FIG. **4**. The target was translated in depth at a uniform rate of 0.5 mm/hr. The signal moves through peaks (maximum-minimum-maximum) every half wavelength of 1.6 mm. FIG. **7** shows a total of six such fringes going through a total distance of 9.6 mm. In an actual borehole application on a melt surface target, the fringes might not be as uniform because of non-flat, fluctuating surfaces and/or non-uniform penetration rates. For instance, if part of the surface at the bottom of the borehole varies in height by about a ¼ of a wavelength or more at the probe frequency, then it may reflect part of the probe signal out of phase with the rest of the probe signal, reducing the fringe peak signal strength (and fringe contrast).

[0060] FIG. **8** shows reflectometer signals from a crater melted into a basalt rock surface by a 28 GHz drilling beam having a power of about 4.5 kW in about a 40 mm diameter incident on the surface of the basalt. This system uses two reflectometer beams at different frequencies: one at the drilling beam frequency of 28 GHz that is picked off from returned drilling beam radiation and a separate 94 GHz monitor beam (e.g., both FIG. **1**A and FIG. **1**B together). The top plot is the reflectometer signal from the 94 GHz monitor **160** and the bottom plot is the reflectometer signal from a 28 GHz Schottky diode detector/mixer **184** coupled to the reflected power isolator **180** (FIG. **1**B) that also samples the forward high-power MMW radiation. The fringe peaks are not as ideal as shown for a laboratory test from a flat solid surface. The plots show about six 94 GHz peaks to about two 28 GHz peaks in direct portion to the probe signal wavelengths ratio for formation of a crater about 10 mm deep.

[0061] FIG. **9** shows a cross section of the basalt crater **910** created by exposure of solid basalt rock **920** to the drilling beam, as described in connection with FIG. **8**. The crater dept is about 10 mm. Molten rock has pooled and solidified in the crater filling a substantial portion of the drilled region. Having different reflectometer probe signals at different frequencies can mitigate uncertainty with monitoring non-ideal reflectometer signals. For example, detecting peaks and cross-correlating the number of detected peaks in accordance with the probe wavelength ratio of the different probe signals can increase certainty in depth measurements.

[0062] Apparatus for measuring the depth or rate of penetration of a borehole drilled with a millimeter-wave directed-energy drilling beam can be implemented and/or included in drilling systems in various configurations. Example configurations are listed below. Corresponding methods of measuring depth or rate of penetration can also be implemented.

[0063] (1) A system for drilling a borehole, the system comprising: a source to generate a millimeter-wave radiation; a transmission line, coupled to the source, to guide the millimeter-wave radiation to a bottom of the borehole and to form a millimeter-wave drilling beam in a region at a distal end of the transmission line; a rate-of-penetration/depth monitor, coupled to the transmission line, to monitor a depth and/or a rate-of-penetration of the borehole; and a beam combiner, coupled to the transmission line and to the rate-of-penetration/depth monitor, to couple a probe signal into the transmission line for transmission to the bottom of the borehole and to couple a returned probe signal, generated by reflection and/or scattering of the probe signal from the bottom of the borehole, from the transmission line to the rate-of-penetration/depth monitor.

[0064] (2) The system of configuration (1), wherein the rate-of-penetration/depth monitor is configured to operate as a reflectometer.

[0065] (3) The system of configuration (1), wherein the rate-of-penetration/depth monitor is configured to operate as a frequency-modulated radar.

[0066] (4) The system of configuration (1), wherein the rate-of-penetration/depth monitor is configured to operate as a pulse-modulated time-of-flight radar.

[0067] (5) The system of any one of configurations (1) through (4), wherein the rate-of-penetration/depth monitor is configured to generate the probe signal at a frequency different than a frequency of the millimeter-wave radiation.

[0068] (6) The system of any one of configurations (1) through (5), wherein the beam combiner is configured to direct a portion of the millimeter-wave radiation returned from the bottom of the borehole to the rate-of-penetration/depth monitor as the returned probe signal.

[0069] (7) The system of any one of configurations (1) through (6), wherein the beam combiner comprises a miter mirror to reflect the millimeter-wave radiation around a bend of the transmission line and having a hole therein to pass the probe signal.

[0070] (8) The system of any one of configurations (1) through (7), further comprising: a temperature monitor to receive radiation indicative of a temperature of the borehole; and a small-signal beam combiner, coupled to the transmission line, to couple the radiation from the transmission line, wherein the radiation propagates along the transmission line with the returned probe signal.

[0071] (9) A method of measuring a depth and/or a rate of penetration of a borehole drilled with millimeter-wave radiation guided by a transmission line to a bottom of the borehole and formed into a millimeter-wave drilling beam, the method comprising: coupling a probe signal into the transmission line; guiding the probe signal to the bottom of the borehole with the transmission line, at least a portion of the probe signal reflecting and/or scattering from the bottom of the borehole as a returned probe signal; guiding the returned probe signal from the bottom of the borehole with the transmission line; coupling the returned probe signal out of the transmission line; mixing the returned probe signal with a local oscillator to produce an intermediate frequency signal; and determining the depth and/or the rate of penetration of the borehole from an amplitude and/or a frequency of the intermediate frequency signal.

[0072] (10) The method of (9), further comprising modulating an amplitude of the probe signal and determining the depth and/or the rate of penetration of the borehole is based on the amplitude of the intermediate frequency signal.

[0073] (11) The method of (9), further comprising modulating a frequency of the probe signal and determining the depth and/or the rate of penetration of the borehole is based on the frequency of the intermediate frequency signal.

[0074] (12) The method of (9), further comprising forming the probe signal into at least one pulse; and determining the depth and/or the rate of penetration of the borehole based on a time of flight of the at least one pulse.

[0075] (13) The method of any one of (9) through (12), further comprising generating the probe signal at a frequency that is different than a frequency of the millimeter-wave radiation.

[0076] (14) The method of any one of (9) through (12), further comprising forming the probe signal from a portion of the millimeter-wave radiation.

[0077] (15) The method of any one of (9) through (14), further comprising receiving radiation indicative of a temperature of the bottom of the borehole via the transmission line.

[0078] (16) A method of forming a borehole with a millimeter-wave drilling beam and determining a depth and/or a rate of penetration of the borehole, the method comprising: coupling millimeter-wave radiation into a transmission line; coupling a probe signal into the transmission line; guiding the millimeter-wave radiation and the probe signal to a bottom of the borehole with the transmission line; forming the millimeter-wave drilling beam at a distal end of the transmission line; increasing a depth of the borehole with the millimeter-wave drilling beam; guiding a returned probe signal from the bottom of the borehole with the transmission line, the returned probe signal being at least a portion of the probe signal reflecting and/or scattering from the bottom of the borehole; coupling the returned probe signal out of the transmission line; mixing the returned probe signal with a local oscillator to produce an intermediate frequency signal; and determining the depth and/or the rate of penetration of the borehole from an amplitude and/or a frequency of the intermediate frequency signal.

[0079] (17) The method of (16), further comprising modulating an amplitude or frequency of the probe signal and determining the depth and/or the rate of penetration of the borehole is based on the amplitude of the intermediate frequency signal.

[0080] (18) The method of (16), further comprising forming the probe signal into at least one pulse; and determining the depth and/or the rate of penetration of the borehole based on a time of flight of the at least one pulse.

[0081] (19) The method of any one of (16) through (18), further comprising: coupling a first temperature signal that is emitted from the bottom of the borehole into the transmission line while drilling with the millimeter-wave drilling beam; coupling the first temperature signal from the transmission line to a temperature monitor; determining a first temperature with the temperature monitor; adjusting an amount of power in the millimeter wave radiation based on the first temperature; ceasing the guiding of the millimeter-wave radiation to the bottom of the borehole; allowing the bottom of the borehole to reach a lower temperature; coupling at least a second temperature signal that is emitted from the bottom of the borehole into the transmission line; coupling at least the second temperature signal from the transmission line to a temperature monitor; determining at least a second temperature with the temperature monitor; and determining whether the drilling has reached a sufficient depth to access geothermal heat based on at least the second temperature.

4. Conclusion

[0082] All parameters, dimensions, materials, and configurations described herein are meant to be exemplary and the actual parameters, dimensions, materials, and/or configurations will depend upon the specific application or applications for which the inventive teachings is/are used. It is to be understood that the foregoing embodiments are presented primarily by way of example and that, within the scope of the appended claims and equivalents thereto, inventive embodiments may be practiced otherwise than as specifically described and claimed. Inventive embodiments of the present disclosure are directed to each individual feature, system, article, material, kit, and/or method described herein. In addition, any combination of two or more such features, systems, articles, materials, kits, and/or methods, if such features, systems, articles, materials, kits, and/or methods are not mutually inconsistent, is included within the inventive scope of the present disclosure.

[0083] Also, various inventive concepts may be embodied as one or more methods, of which at least one example has been provided. The acts performed as part of the method may in some instances be ordered in different ways. Accordingly, in some inventive implementations, respective acts of a given method may be performed in an order different than specifically illustrated, which may include performing some acts simultaneously (even if such acts are shown as sequential acts in illustrative embodiments).

[0084] All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety.

[0085] All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

[0086] The indefinite articles “a” and “an,” as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean “at least one.”

[0087] The phrase “and/or,” as used herein in the specification and in the claims, should be understood to mean “either or both” of the elements so conjoined, i.e., elements that are conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with “and/or” should be construed in the same fashion, i.e., “one or more” of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the “and/or” clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to “A and/or B”, when used in conjunction with open-ended language such as “comprising” can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

[0088] As used herein in the specification and in the claims, “or” should be understood to have the same meaning as “and/or” as defined above. For example, when separating items in a list, “or” or “and/or” shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as "only one of" or "exactly one of," or, when used in the claims, "consisting of," will refer to the inclusion of exactly one element of a number or list of elements. In general, the term "or" as used herein shall only be interpreted as indicating exclusive alternatives (i.e., "one or the other but not both") when preceded by terms of exclusivity, such as "either," "one of," "only one of," or "exactly one of." "Consisting essentially of," when used in the claims, shall have its ordinary meaning as used in the field of patent law.

[0089] As used herein in the specification and in the claims, the phrase "at least one," in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase "at least one" refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, "at least one of A and B" (or, equivalently, "at least one of A or B," or, equivalently "at least one of A and/or B") can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

[0090] In the claims, as well as in the specification above, all transitional phrases such as "comprising," "including," "carrying," "having," "containing," "involving," "holding," "composed of," and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases "consisting of" and "consisting essentially of" shall be closed or semi-closed transitional phrases, respectively, as set forth in the United States Patent Office Manual of Patent Examining Procedures, Section 2111.03.

1. A system for drilling a borehole, the system comprising:

a source to generate a millimeter-wave radiation;

a transmission line, coupled to the source, to guide the millimeter-wave radiation to a bottom of the borehole and to form a millimeter-wave drilling beam in a region at a distal end of the transmission line;

a rate-of-penetration/depth monitor, coupled to the transmission line, to monitor a depth and/or a rate-of-penetration of the borehole; and

a beam combiner, coupled to the transmission line and to the rate-of-penetration/depth monitor, to couple a probe signal into the transmission line for transmission to the bottom of the borehole and to couple a returned probe signal, generated by reflection and/or scattering of the probe signal from the bottom of the borehole, from the transmission line to the rate-of-penetration/depth monitor.

2. The system of claim **1**, wherein the rate-of-penetration/depth monitor is configured to operate as a reflectometer.

3. The system of claim **1**, wherein the rate-of-penetration/depth monitor is configured to operate as a frequency-modulated radar.

4. The system of claim **1**, wherein the rate-of-penetration/depth monitor is configured to operate as a pulse-modulated time-of-flight radar.

5. The system of claim **1**, wherein the rate-of-penetration/depth monitor is configured to generate the probe signal at a frequency different than a frequency of the millimeter-wave radiation.

6. The system of claim **1**, wherein the beam combiner is configured to direct a portion of the millimeter-wave radiation returned from the bottom of the borehole to the rate-of-penetration/depth monitor as the returned probe signal.

7. The system of claim **1**, wherein the beam combiner comprises a miter mirror to reflect the millimeter-wave radiation around a bend of the transmission line and having a hole therein to pass the probe signal.

8. The system of claim **1**, further comprising:

a temperature monitor to receive radiation indicative of a temperature of the borehole; and

a small-signal beam combiner, coupled to the transmission line, to couple the radiation from the transmission line, wherein the radiation propagates along the transmission line with the returned probe signal.

9. A method of measuring a depth and/or a rate of penetration of a borehole drilled with millimeter-wave radiation guided by a transmission line to a bottom of the borehole and formed into a millimeter-wave drilling beam, the method comprising:

coupling a probe signal into the transmission line;

guiding the probe signal to the bottom of the borehole with the transmission line, at least a portion of the probe signal reflecting and/or scattering from the bottom of the borehole as a returned probe signal;

guiding the returned probe signal from the bottom of the borehole with the transmission line;

coupling the returned probe signal out of the transmission line;

mixing the returned probe signal with a local oscillator to produce an intermediate frequency signal; and

determining the depth and/or the rate of penetration of the borehole from an amplitude and/or a frequency of the intermediate frequency signal.

10. The method of claim **9**, further comprising:

modulating an amplitude of the probe signal and determining the depth and/or the rate of penetration of the borehole is based on the amplitude of the intermediate frequency signal.

11. The method of claim **9**, further comprising:

modulating a frequency of the probe signal and determining the depth and/or the rate of penetration of the borehole is based on the frequency of the intermediate frequency signal.

12. The method of claim **9**, further comprising:

forming the probe signal into at least one pulse; and

determining the depth and/or the rate of penetration of the borehole based on a time of flight of the at least one pulse.

13. The method of claim **9**, further comprising:

generating the probe signal at a frequency that is different than a frequency of the millimeter-wave radiation.

14. The method of claim **9**, further comprising forming the probe signal from a portion of the millimeter-wave radiation.

15. The method of claim **9**, further comprising:

receiving radiation indicative of a temperature of the bottom of the borehole via the transmission line.

16. A method of forming a borehole with a millimeter-wave drilling beam and determining a depth and/or a rate of penetration of the borehole, the method comprising:

coupling millimeter-wave radiation into a transmission line;

coupling a probe signal into the transmission line;

guiding the millimeter-wave radiation and the probe signal to a bottom of the borehole with the transmission line;

forming the millimeter-wave drilling beam at a distal end of the transmission line;

increasing a depth of the borehole with the millimeter-wave drilling beam;

guiding a returned probe signal from the bottom of the borehole with the transmission line, the returned probe signal being at least a portion of the probe signal reflecting and/or scattering from the bottom of the borehole;

coupling the returned probe signal out of the transmission line;

mixing the returned probe signal with a local oscillator to produce an intermediate frequency signal; and

determining the depth and/or the rate of penetration of the borehole from an amplitude and/or a frequency of the intermediate frequency signal.

17. The method of claim **16**, further comprising:

modulating an amplitude or frequency of the probe signal and determining the depth and/or the rate of penetration of the borehole is based on the amplitude of the intermediate frequency signal.

18. The method of claim **16**, further comprising:

forming the probe signal into at least one pulse; and

determining the depth and/or the rate of penetration of the borehole based on a time of flight of the at least one pulse.

19. The method of claim **16**, further comprising:

coupling a first temperature signal that is emitted from the bottom of the borehole into the transmission line while drilling with the millimeter-wave drilling beam;

coupling the first temperature signal from the transmission line to a temperature monitor;

determining a first temperature with the temperature monitor;

adjusting an amount of power in the millimeter wave radiation based on the first temperature;

ceasing the guiding of the millimeter-wave radiation to the bottom of the borehole;

allowing the bottom of the borehole to reach a lower temperature;

coupling at least a second temperature signal that is emitted from the bottom of the borehole into the transmission line;

coupling at least the second temperature signal from the transmission line to a temperature monitor;

determining at least a second temperature with the temperature monitor; and

determining whether the drilling has reached a sufficient depth to access geothermal heat based on at least the second temperature.

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