

## ( 12 ) United States Patent

## Doucet

## (54) REDUCTION OF FARADAY EFFECT IN OPTICAL GROUND WIRE (OPGW) CABLES

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- $(52)$  U.S. Cl. CPC ......... **G02B 6/4417** (2013.01); **G02B 6/4413** (2013.01)
- ( $2013.01$ )<br>(58) Field of Classification Search None See application file for complete search history.

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(21) Appl. No.: 15/281,761 Primary Examiner — Hemang Sanghavi (74) Attorney, Agent, or  $Firm$  — Integral Intellectual (22) Filed: Sep. 30, 2016 Property Inc.; Miriam Paton; Amy Scouten

## ABSTRACT

New optical ground wire (OPGW) cable structures are proposed. These OPGW cables are designed to reduce or minimize the net magnetic field  $B_{\parallel}^{A,BT}$  parallel to the direction 2 of light propagation resulting from a lightning strike on the cable. A reduction in the net magnetic field  $B_{\parallel}^{NET}$ parallel to the direction  $\hat{z}$  of light propagation yields a reduction in the amount and speed of state of polarization (SOP) rotation resulting from a lightning strike on the cable due to the Faraday effect. OPGW cables constructed according to these new OPGW cable structures fulfill their dual ning strikes and to support coherent optical communications.

### 174/115 **12 Claims, 15 Drawing Sheets**























**FIG. 7** 



**FIG. 8** 







**FIG. 11** 













and distribution are high-voltage conductors suspended by towers. Cables of optical ground wire (OPGW), also known as "optical fiber composite overhead ground wire", are run 15 FIG. 1, FIG. 2, FIG. 3, FIG. 4, FIG. 5 and FIG. 6 are between the tops of the towers, serving to ground the towers cut-away illustrations of various example opt and to shield the high-voltage conductors from lightning wire (OPGW) cables;<br>strikes. FIG. 7 shows an example OPGW cable suspended atop

The optical fibers within an OPGW cable can be used for electric power transmission towers;<br>ta communications. Information can be encoded using the  $20$  FIG. **8** shows the geometry of a segment of wire strand data communications. Information can be encoded using the  $20$  FIG. **8** shows the geometry of a segment of ware strangular a single coil loop around the cable; amplitude, the phase, and the polarization of the light that is representing a single coil loop around the cable;<br> $FIG. 9 (PRIOR ART)$  shows a cross-section of an example

plane of polarization which is linearly proportional to the 25 layer;<br>component of the magnetic field in the direction of light FIG. 10 shows a cross-section of an example roughlypropagation. The magnetic field in the magnetic field in the direction of an example roughly propagation of an equal number of an example roughly propagation.

carries one or more optical fibers, the core element sur-<br>
rounded by N layers of concentric stranded wires, where N FIG. 12 shows a cross-section of an example 4-layer is an integer and  $N \ge 2$ . The wires are stranded in a right-hand, 35 84-strand OPGW cable, having all of its strands of high clockwise (CW) lay direction in M of the layers, and the electrical conductivity wire in its ou provides the proposed OPGW cable with mechanical stabil-40 high electrical conductivity wire in its clockwise stranded ity and integrity, including mechanical strength, crush resis-<br>layers and in its counter-clockwise stra ity and integrity, including mechanical strength, crush resis-<br>tance, and bending flexibility.<br>FIG. 14 shows a cross-section of another e

amplitude, the phase, and the polarization of the light that is 45 reverse to the wires of the other two layers, having equal propagated through the optical fibers. Current flow in the numbers of strands of high electrical in a net magnetic field  $B_1^{NET}$  parallel to the direction  $\hat{z}$  of light propagation. Due to the Faraday effect, the net mag-<br>netic field  $B_{\parallel}^{NET}$  parallel to the direction  $\hat{z}$  of light propa- 50 adjusted roughly-balanced 84-strand OPGW cable, with netic field  $\tilde{B}_{\parallel}^{NET}$  parallel to the direction  $\hat{z}$  of light propasion causes a change in the light's state of polarization gation causes a change in the light's state of polarization wires of its innermost layer and its outer layer stranded in a (SOP). If the magnetic field changes quickly, there will be an lay direction reverse to the wires o equivalent rate of change on the optical signal's SOP. having equal numbers of strands of high electrical conduc-<br>Unexpected changes to the optical signal's SOP, especially tivity wire in its clockwise stranded layers and high speed SOP transients that occur when lightning strikes 55 clockwise stranded layers.<br>the cable, can be disruptive to coherent optical communi-<br>cations and may result in impairments within the coherent DETAILED DESCRIP cations and may result in impairments within the coherent optical communications system.

This document proposes new OPGW cable structures Mechanical Structure of OPGW Cable signed to reduce or minimize the net magnetic field  $B_n^{NET}$  60 Example optical ground wire (OPGW) cables as proposed designed to reduce or minimize the net magnetic field  $B_{\parallel}^{NET}$  60 Example optical ground wire (OPGW) cables as proposed parallel to the direction  $\hat{z}$  of light propagation resulting from in this document are construc parallel to the direction  $\hat{z}$  of light propagation resulting from a lightning strike on the cable. A reduction in the net a lightning strike on the cable. A reduction in the net carries one or more optical fibers, the core element sur-<br>magnetic field  $B_{\parallel}^{NET}$  parallel to the direction  $\hat{z}$  of light rounded by N layers of concentric stra magnetic field B  $NET$  parallel to the direction  $\hat{z}$  of light rounded by N layers of concentric stranded wires, where N propagation yields a reduction in the amount and speed of is an integer and N $\geq$ 2. The wires are SOP rotation resulting from a lightning strike on the cable 65 clockwise (CW) lay direction in M of the layers, and the due to the Faraday effect. OPGW cables constructed accord-<br>wires are stranded in a left-hand, countering to these new OPGW cable structures fulfill their dual lay direction in the remaining (N-M) layers, where M is an

REDUCTION OF FARADAY EFFECT IN function to shield the high-voltage conductors from light-<br>OPTICAL GROUND WIRE (OPGW) CABLES ining strikes and to support coherent optical communicaning strikes and to support coherent optical communications.

TECHNICAL FIELD The reduction or minimization of the net magnetic field  $B_{\parallel}^{NET}$  is achieved by designing the new OPGW structure to balance or equalize total contributions to the net magnetic This document relates to the technical field of optical balance or equalize total contributions to the net magnetic ground wire (OPGW), also known as "optical fiber com-<br>posite overhead ground wire". the right-hand, CW la the right-hand, CW lay direction and total contributions to the net magnetic field  $B_{\parallel}^{NET}$  from the remaining (N-M) BACKGROUND 10 layers whose wires are stranded in the left-hand, CCW lay<br>direction.<br>d distribution are high-voltage conductors suspended by BRIEF DESCRIPTION OF THE DRAWINGS

cut-away illustrations of various example optical ground wire (OPGW) cables;

There is a well-known interaction between light and a 2-layer conventional 30-strand OPGW cable, having all of magnetic field. The Faraday effect causes a rotation of the its strands of high electrical conductivity wire in its strands of high electrical conductivity wire in its outer laver:

> strands of high electrical conductivity wire in its inner layer SUMMARY and in its outer layer;<br>30 FIG. 11 shows a cross-section of an example low-k

Example optical ground wire (OPGW) cables as proposed adjusted roughly-balanced OPGW cable, having an equal<br>in this document are constructed of a core element that number of strands of high electrical conductivity wire in number of strands of high electrical conductivity wire in its inner layer and in its outer layer;

lay direction in the remaining  $(N-M)$  layers, where M is an balanced 84-strand OPGW cable with alternately reversed integer, M is less than N, and  $M\geq 1$ . Concentric stranding lay direction stranding, having equal number

tance, and bending flexibility.<br>The optical fibers of the OPGW cable can be used for data roughly-balanced 84-strand OPGW cable, with wires of its<br>communications. Information can be encoded using the innermost layer and it clockwise stranded layers and in its counter-clockwise stranded layers; and

tivity wire in its clockwise stranded layers and in its counter-

ity and integrity, including mechanical strength, crush resis-<br>
ization (SOP) Transients<br>
ization (SOP) Transients

cut-away illustrations of various example OPGW cables 100 atop electric power transmission towers 702. The cable 700<br>as proposed in this document. In these examples, the cable is susceptible to lightning strikes, as illust as proposed in this document. In these examples, the cable is susceptible to lightning strikes, as illustrated by a light-<br>100 is constructed of a core element 102 that carries one or hing bolt 704. Lightning coming into c 100 is constructed of a core element 102 that carries one or ning bolt 704. Lightning coming into contact with the cable<br>more ortical fibers 104. A direction  $\hat{\sigma}$  of light proposation 700 causes current to flow in the c more optical fibers 104. A direction  $\hat{z}$  of light propagation  $\frac{700}{10}$  causes current to now in the cable 700. In a typical case

first helix structure around the core element 102. The wire  $20$  rounded by N layers of concentric stranded wires, where N strands of a second layer 108 form a multi-stranded second is an integer and  $N \ge 2$ . The wires ar helix structure around the first layer 106. If a third layer 110 CW lay direction in M of the layers, and the wires are exists, the wire strands of the third layer 110 form a stranded in a left-hand, CCW lay direction in t multi-stranded third helix structure around the second layer (N-M) layers, where M is an integer, M is less than N, and 108. If a fourth layer 112 exists, the wire strands of the fourth 25 M $\geq$ 1.<br>layer 112 form a multi-stranded helix structure around the The optical fibers of the cable 700 can be used for data<br>communications. Information

CCW lay direction in the remaining  $(N-M)$  layers, where M 30 is an integer, M is less than N, and  $M \ge 1$ . For a two-layer is an integer, M is less than N, and M $\geq$ 1. For a two-layer layers results in a net magnetic field  $B_1^{NET}$  parallel to the cable, the lay direction of the wire strands of the first layer direction  $\hat{z}$  of light prop cable, the lay direction of the wire strands of the first layer<br>106 is reverse to the lay direction of the wire strands of the<br>106 is reverse to the lay direction of the wire strands of the<br>106 is reverse to the lay direc of the wire strands of one of the layers is reverse to the lay 35 polarization (SOP). If the magnetic field changes quickly, direction of the wire strands of the other two layers. For a there will be an equivalent rate of layers is reverse to the lay direction of the wire strands of the other two layers, or the lay direction of the wires of one layer

FIG. 2 illustrates a left-hand, CCW lay direction for the 45 propagates before it is grounded at the tower.<br>wire strands of the first layer 106 and a right-hand, CW lay<br>direction for the optical signal's SOP, espe-<br>cially

wire strands of the first layer  $106$ , a right-hand, CW lay<br>direction for the wire strands of the second layer  $108$  and a  $\epsilon_0$  coherent optical communications system. direction for the wire strands of the second layer 108, and a 50 concreting optical communications system.<br>Left hand CCW lay direction for the wire strands of the third Current Flow in Single Loop Coil and in Helix Wire left-hand, CCW lay direction for the wire strands of the third Strand layer 110.<br>EIG 4 illustrates a left hand CCW lay direction for the Current flowing in a single loop coil (zero pitch) about an

wire strands of the first layer 106 and for the wire strands of axis is perpendicular to the axis, and the magnetic field<br>the second layer 108, and a right hand CW lay direction for 55 created by that current flow is paral the second layer 108, and a right-hand, CW lay direction for 55 the wire strands of the third layer 110.

FIG. 5 illustrates a four-layer cable with alternating lay directions. There is a right-hand, CW lay direction for the wire strands of the first layer 106 and for the wire strands of the third layer 110, and a left-hand, CCW lay direction for 60 the wire strands of the second layer 108 and for the wire strands of the fourth layer 112.

FIG. 6 illustrates a four-layer cable with the two middle where the magnetic permeability  $\mu_0$  is a constant equal to layers having a reverse lay direction to the inner layer and  $4\pi \times 10^{-7}$  henry per meter, I represe to the outer layer. There is a right-hand, CW lay direction for  $65$  the wire strands of the first layer 106 and for the wire strands

integer, M is less than N, and M $\geq$ 1. Concentric stranding for the wire strands of the second layer 108 and for the wire provides the proposed OPGW cable with mechanical stabil-<br>strands of the third layer 110.

tance, and bending flexibility.<br>FIG. 1. FIG. 2. FIG. 3. FIG. 4. FIG. 5 and FIG. 6 are  $5$  FIG. 7 shows an example OPGW cable 700 suspended FIG. 1, FIG. 2, FIG. 3, FIG. 4, FIG. 5 and FIG. 6 are 5 FIG. 7 shows an example OPGW cable 700 suspended Flaway illustrations of various example OPGW cable 700 within the optical fibers 104 is shown.<br>
The cables shown in FIG. 1 and FIG. 2 have two layers<br>
of concentric stranded wires. The cables shown in FIG. 3<br>
and FIG. 4 have three layers of concentric stranded wires.<br>
The cabl

stranded wires.<br>The wire strands of a first layer 106 form a multi-stranded<br>first helix structure around the core element 102. The wire <sub>20</sub> rounded by N layers of concentric stranded wires, where N

ird layer 110.<br>The wires are stranded in a right-hand, CW lay direction amplitude, the phase, and the polarization of the light that is The wires are stranded in a right-hand, CW lay direction amplitude, the phase, and the polarization of the light that is in M of the layers, and the wires are stranded in a left-hand, propagated through the optical fibers. propagated through the optical fibers. As explained in more detail below, the current flow in the wire strands of the N light propagation causes a change in the light's state of polarization (SOP). If the magnetic field changes quickly, signal's SOP. The rotation of the optical signal's SOP, in units of radians, is given by Equation 1:

$$
SOP_{delta} = f^2 \times V_t \times L \times B_{\parallel}^{NET}
$$
 (1)

is reverse to the lay direction of the wire strands of the other 40<br>three f is the optical signal frequency (approximately<br> $FIG$ , 1 illustrates a right-hand CW lay direction for the  $193 \times 10^{12}$  Hz), V<sub>t</sub> is the Verdet c FIG. 1 illustrates a right-hand, CW lay direction for the  $\frac{193\times10}{120\times10^{11}}$  Hz), V<sub>t</sub> is the Verdet constant (equal to 1.42×10  $\frac{193\times10}{120\times10^{11}}$  radians/(meter Tesla Hz<sup>2</sup>), and L represents the length of th wire strands of the first layer  $106$  and a left-hand, CCW lay radians/(meter restance), and L represents the length of the vira strands of the second layer  $108$  rath of the cable 700 through which the lightning current direction for the wire strands of the second layer  $108$ . path of the cable 700 through which the lightning current is grounded at the tower.

direction for the wire strands of the second layer 108.<br>EIG 2 illustrates a left band CCW lay direction for the strikes the cable 700, can be disruptive to coherent optical FIG. 3 illustrates a left-hand, CCW lay direction for the strikes the cable 700, can be disruptive to coherent optical<br>communications and may result in impairments within the

FIG. 4 illustrates a left-hand, CCW lay direction for the Current flowing in a single loop coil (zero pitch) about an exis are permetered in a single loop coil (zero pitch) about an exis are permetered in a single loop coi strength of that magnetic field within the loop is given by Equation 2:

$$
B = \frac{\mu_0 I}{\pi D} \tag{2}
$$

 $4\pi \times 10^{-7}$  henry per meter, I represents the current flowing in the single loop coil, and  $\pi D$  represents the circumference of the wire strands of the first layer 106 and for the wire strands the single loop coil. If the current flows clockwise about the of the fourth layer 112, and a left-hand, CCW lay direction axis, the resulting magnetic field axis, the resulting magnetic field is in the direction of the the resulting magnetic field is opposite to the direction of the light propagation can be expressed as a sum of contributions axis.

Each wire strand is a helix that can be considered as a partially-unwrapped coil, because there is a non-zero pitch 5 to the helix. FIG. 8 shows a portion of wire strand of a helix of circumference  $\pi$ D and pitch p unwound to show trigonometric dimensions . The pitch p is the distance for a wire strand to complete a full turn (single loop) around the core element. An angle  $\alpha$  is equal to arctan( $\pi D/p$ ). Current I flows 10<br>in the wire strand and has a current component I<sub>1</sub> that is<br>perpendicular to the direction  $\hat{z}$  of light propagation. The<br>strength of the current co strength of the current component  $I_{\perp}$  represents the effective corresponding coefficient  $\alpha_{layer}$  that is equal to +1 for one current component cround a single loop about the oxis of the state of the state of the stat current component around a single loop about the axis of the lay direction (e.g. the right-hand, CW lay direction) and that cable, is given by Equation 3:

$$
I_1 = I \times \sin \alpha = I \times \sin(\arctan(\pi D/p))
$$
\n(3)

The current in the core element 102 flows parallel to the<br>direction  $\hat{z}$  of light propagation in the one or more optical<br>fibers, and therefore the magnetic field created around the<br>core element 102 by that current flow field created by the flow of current in the core element  $102$  This document proposes new OPGW cable structures<br>has no effect on the polarization state of the light carried by designed to reduce or minimize the net magnet has no effect on the polarization state of the light carried by designed to reduce or minimize the net magnetic field  $B_{\parallel}$  the optical fibers.

magnetic field is created around each of the wire strands. magnetic field  $B_1^{22}$  parallel to the direction  $\overline{z}$  of light<br>The wire strands are not parallel to the direction  $\hat{z}$  of light propagation yields a redu The wire strands are not parallel to the direction  $\hat{z}$  of light propagation yields a reduction in the amount and speed of propagation in the one or more optical fibers, and therefore SOP rotation resulting from a ligh propagation in the one or more optical fibers, and therefore SOP rotation resulting from the current flowing in each wire strand has a component  $I_{\perp 35}$  due to the Faraday effect. that is perpendicular to the direction  $\hat{z}$  of light propagation.  $\overline{z}$  OPGW cables according to the new OPGW cable structure . The current component I, that is perpendicular to the direction in the structure struct The current component  $I_{\perp}$  that is perpendicular to the direc-<br>tion  $\hat{z}$  of light propagation creates a corresponding magnetic more optical fibers, the core element surrounded by N layers field component  $\hat{B}_{\parallel}$  that is parallel to the direction  $\hat{z}$  of light of concentric stranded wires, where N is an integer and N≥2.<br>propagation. At the center of the core element, the strength  $\frac{40}{40}$  The wires

$$
B_{\parallel} = \frac{\mu_0 I \times \sin\left(\arctan\left(\frac{\pi D}{p}\right)\right)}{\pi D} \tag{4}
$$

having a left-hand, CCW lay direction will result in a  $50<sup>1</sup>$  layers whose means in the left is nonellal to and ennough direction. magnetic field component  $B_{\parallel}$  that is parallel to and opposite direction.<br>
Equation 5 can be rewritten as given in Equation 6: to the direction 2 of light propagation, and current flowing in wire strands of a layer having a right-hand, CW lay direction will result in a magnetic field component  $B_{\parallel}$  that is parallel to and coincident to the direction  $\hat{z}$  of light propa-ss gation. Stated differently, the magnetic field components  $B<sub>II</sub>$ created by the wires stranded in one lay direction counteract the magnetic field components  $B_{\parallel}$  created by the wires stranded in the reverse lay direction.

There is a net magnetic field B  $_{\parallel}^{NET}$  parallel to the direction 60 To balance or equalize the contributions, the new OPGW  $\hat{z}$  of light propagation that has contributions from the current structure should aim to h 2 of light propagation that has contributions from the current structure should aim to have the first sum in Equation 6 flowing in each of the wire strands of the N layers. As equal to the second sum in Equation 6. This ba flowing in each of the wire strands of the N layers. As equal to the second sum in Equation 6. This balance or explained above, the contributions to the net magnetic field equalization of contributions is possible because  $B_{\parallel}^{NET}$  due to current flowing in wire strands of a layer having strands comprise wire strands of different electrical conduc-<br>a left-hand, CCW lay direction counteract the contributions 65 tivity  $\kappa$ . Wire strands h a left-hand, CCW lay direction counteract the contributions 65 tivity K. Wire strands having relatively higher electrical to the net magnetic field  $B_1^{NET}$  due to current flowing in wire conductivity K will contribute mo to the net magnetic field B  $N^{ET}$  due to current flowing in wire strands of a layer having a right-hand, CW lay direction.

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axis. If the current flows counter-clockwise about the axis, The net magnetic field  $B_{\parallel}^{NET}$  parallel to the direction  $\hat{z}$  of the resulting magnetic field is opposite to the direction of the light propagation can be as given by Equation 5:

$$
N_{\parallel}^{NET} = \sum_{layer=1}^{N} \alpha_{layer} B_{layer}
$$
 (5)

 $I_1 = I_2 = I_3 = -I_4 = -I_5 = -I_6 = -I_7 = -I_7 = -I_8 = -I_7 = -I_8 = -I_7 = -I_8 = 0$ <br>CCW lay direction).<br>Current Flow in Core Element and Wire Strands Due to<br>B<sub>11</sub><sup>NET</sup>=B<sub>1</sub>-B<sub>2</sub>. For the cable illustrated in FIG. **2**, Equation Lightning Strike<br>Lightning coming into contact with the cable 700 causes  $\frac{1}{20}$  3, Equation 5 becomes  $B_1^{NET} = -B_1 + B_2$ . For the cable illustrated in FIG.<br>Current to flow in the core element 102 and in the wire<br>illust current to flow in the core element 102 and in the wire illustrated in FIG. 4, Equation 5 becomes  $B_{\parallel}^{NET} = B_1 - B_2 +$ <br>B<sub>3</sub>. For the cable illustrated in FIG. 5, Equation 5 becomes

a lightning strike on the cable. A reduction in the net As current flows in the wire strands of the N layers, a <sup>a</sup> a lightning strike on the cable. A reduction in the net agnetic field is created around each of the wire strands. Magnetic field  $B_1^{NET}$  parallel to the direct

direction  $\hat{z}$  of light propagation is given by Equation 4: CCW lay direction in the remaining (N–M) layers, where M<br>is an integer, M is less than N, and M≥1.

The reduction or minimization of the net magnetic field Br is achieved by designing the new OPGW structure to  $H_3$  Br is achieved by designing the new OPGW structure to balance or equalize total contributions to the net magnetic field  $B_{\parallel}^{NET}$  from the M layers whose wires are stranded in the right-hand, CW lay direction and total contributions to the net magnetic field  $B_0^{NET}$  from the remaining (N–M) Accordingly, current flowing in wire strands of a layer the net magnetic field  $B_{\parallel}$  from the remaining (N-M) and  $\mu$  of  $\mu$  and  $\mu$  and  $\mu$  is the net magnetic field  $B_{\parallel}$  from the remaining (N-M) and  $\mu$  magnet

$$
B_{\shortparallel}^{NET} = \sum_{\substack{CW \ layer = 1 \\ \text{wire standard} \\ \text{in } CW \ layer \text{discrete} \\ \text{for } W \text{ layer} = \text{true}}}^{M} B_{CW \ layer} - \sum_{\substack{CW \ layer = N - M + 1 \\ \text{wire standard} \\ \text{in } CW \ layer \text{ diver}} B_{CCW \ layer}}^{M} B_{CCW \ layer} \tag{6}
$$

equalization of contributions is possible because the wire strands comprise wire strands of different electrical conduc- $B_{\parallel}^{NET}$  than wire strands having relatively lower electrical

relatively high- $\kappa$  wire can be constructed includes alumi-  $\sigma$  ers, where M is an integer, M is less than N, and M $\geq$ 1. The num, aluminum alloy, copper, and copper alloy. A non-cable is "roughly balanced" in that th Thus aluminum is about 22 times more electrically conductivity adjusted" in that the pitch of one or more of the layers is adjusted " in that the pitch of one or more of the layers is of aluminum is much greater than the

relatively high- $\kappa$  wires in the M layers) is equal to the A new OPGW cable structure, referred to in this document as a "roughly-balanced OPGW cable" is proposed. A roughly-balanced OPGW cable is constructed of a core the remaining  $(N-M)$  layers wires one or more optical fibers, the core  $20$  left-hand, CCW lay direction. element surrounded by N layers of concentric stranded A further new OPGW cable structure, referred to in this wires, where N is an integer and N $\geq$ 2. The wires are stranded document as a "low-k adjusted pitch-adjusted r in a right-hand, CW lay direction in M of the layers, and the balanced OPGW cable" is proposed. A low- $\kappa$  adjusted wires are stranded in a left-hand, CCW lay direction in the pitch-adjusted roughly-balanced OPGW cable i remaining  $(N-M)$  layers, where M is an integer, M is less 25 of a core element that carries one or more optical fibers, the than N, and M $\geq 1$ . The cable is "roughly balanced" in that the core element surrounded by N lay than N, and M≥1. The cable is "roughly balanced" in that the<br>core element surrounded by N layers of concentric stranded<br>number of relatively high-k wires stranded in the right-hand,<br>CW lay direction in M of the layers, an

document as a "low-k adjusted roughly-balanced OPGW" cable is " low-k adjusted" in that the number of relatively<br>cable" is proposed. A low x edited roughly belonged 40 low-k wires in one or more of the layers is adjusted s cable" is proposed. A low- $\kappa$  adjusted roughly-balanced 40 OPGW cable is constructed of a core element that carries one or more optical fibers, the core element surrounded by N layers of concentric stranded wires, where N is an integer and  $N\geq 2$ . The wires are stranded in a right-hand, CW lay contributions to the net magnetic field  $B_{\parallel}$  from the direction in M of the layers and the wires are stranded in a transmission of the layers are stranded in direction in M of the layers, and the wires are stranded in a  $45$  remaining (N-M) layers whose wires are stranded in the stranded in the remaining  $(N_M)$  lay. The cable is "pitch-adjusted" left-hand, CCW lay direction in the remaining  $(N-M)$  lay left-hand, CCW lay direction. The cable is " pitch-adjusted " pitch of one or more of the layers is adjusted so ers, where M is an integer, M is less than N, and M $\geq$ 1. The in that the pitch of one or more of the layers is adjusted so cable is "roughly balanced" in that the number of relatively as to better balance or equalize to high-k wires stranded in the right-hand, CW lay direction<br>(which is the total number of strands of relatively high-k 50 stranded in the right-hand, CW lay direction and total<br>wires in the M layers) is equal to the number where  $\frac{1}{2}$  is the fit algebra of the number of relatively<br>high- $\kappa$  wires stranded in the left-hand, CCW lay direction<br>(which is the total number of strands of relatively high- $\kappa$  left-hand, CCW lay direction. (which is the total number of strands of relatively high- $\kappa$ <br>wires in the remaining ( $N - M$ ) layers). The cable is "low- $\kappa$ <br>adjusted" in that the number of relatively low  $K$  wires in one ss.<br>These concepts will now be adjusted" in that the number of relatively low-K wires in one 55 These concepts will now be demonstrated with specific<br>or more of the lowers is adjusted so as to better belonge or examples of 2-layer OPGW cables, such as i or more of the layers is adjusted so as to better balance or examples of 2-layer OPGW cables, such as illustrated in equalize total contributions to the net megnetic field  $R$   $NET$  FIG. 1 and FIG. 2. It will be obvious to equalize total contributions to the net magnetic field  $B_{\parallel}^{NET}$  . FIG. 1 and FIG. 2. It will be obvious to a person of ordinary skills in the art how to adapt the following discussion for from the M layers whose wires are stranded in the right-<br>DPGW cables having more than two layers. Going forward, hand, CW lay direction and total contributions to the net  $\frac{OPGW}{C}$  cables having more than two layers. Going forward, means the first layer 106 will be referred to as "the inner layer 106" magnetic field  $B_{\parallel}^{NET}$  from the remaining (N–M) layers 60 the first layer 106 will be referred to as "the inner layer 106"<br>whose wires are stranded in the left-hand CCW lay direcwhose wires are stranded in the left-hand,  $CCW$  lay direc-<br>tion.  $\frac{1}{2}$  and the sec-<br>layer 108".

document as a "pitch-adjusted roughly-balanced OPGW cable" is proposed. A pitch-adjusted roughly-balanced 65 OPGW cable is constructed of a core element that carries OPGW cable is constructed of a core element that carries where the "outer" magnetic field  $B_{outer}$  parallel to the one or more optical fibers, the core element surrounded by direction  $\hat{z}$  of light propagation is contrib

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conductivity  $\kappa$ . The greater the difference in electrical con-<br>ductivity  $\kappa$ , the greater the difference in contribution to the<br>net magnetic field  $B_{\parallel}^{NET}$ .<br>A non-exhaustive list of example materials from which<br>lef num, aluminum alloy, copper, and copper alloy. A non-<br>
low-k wire can be constructed includes steel and aluminum-<br>
clad steel. For example, the cable may use aluminum strands<br>
and stainless steel strands. The resistivity of aluminum is much greater than the electrical conductivity 15 adjusted so as to better balance or equalize total contribu-<br>of stainless steel:  $\kappa_{A1} >> > \kappa_{step}$ . whose wires are stranded in the right-hand, CW lay direction and total contributions to the net magnetic field  $B_{\parallel}^{NET}$  from the remaining (N–M) layers whose wires are stranded in the

tions to the magnetic field from the relatively low- $\kappa$  wires, 35 relatively mgn- $\kappa$  wires in the M layers) is equal to the<br>and because the magnetic field contributions are affected by<br>and because the magnetic field c better balance or equalize total contributions to the net magnetic field  $B_{\parallel}^{NET}$  from the M layers whose wires are stranded in the right-hand, CW lay direction and total contributions to the net magnetic field  $B_{\parallel}^{NET}$  from the cable is "roughly balanced" in that the number of relatively as to better balance or equalize total contributions to the net high- $\kappa$  wires stranded in the right-hand, CW lay direction and regarded in the right hand  $\kappa$  CW lay direction and tatal

A further new OPGW cable structure, referred to in this In a 2-layer OPGW cable, Equation 1 is rewritten as

$$
SOP_{delta} = f^2 \times V_t \times L\lambda (B_{outer} - B_{inner})
$$
 (7)

direction  $\hat{z}$  of light propagation is contributed by the outer

layer 108 and the "inner" magnetic field  $B_{inner}$  parallel to the current ratio") between the outer layer of wire strands and direction  $\hat{z}$  of light propagation is contributed by the inner layer of wire strands.

Ideally, the outer magnetic field  $B_{outer}$  is equal to the inner magnetic field  $B_{inner}$ , so that the net magnetic field  $B_{\parallel}^{NET}$ magnetic field B<sub>inner</sub>, so that the net magnetic field B<sub>II</sub><sup>NET</sup> <sup>5</sup> of an outer current I<sub>outer</sub> in the wires of the outer layer to an parallel to the direction  $\hat{z}$  of light propagation is equal to inner current I<sub></sub> parallel to the direction 2 of light propagation is equal to inner current  $I_{inner}$  in the wires of the inner layer is within 10 zero. Using Equation 4, this means:

$$
\mu_0 I_{outer} \times \frac{\sin(\arctan(\frac{\pi D_{outer}}{P_{outer}}))}{\pi D_{outer}} = \mu_0 I_{inner} \times \frac{\sin(\arctan(\frac{\pi D_{inner}}{P_{inner}}))}{\pi D_{inner}} \tag{8}
$$

$$
\frac{I_{outer}}{I_{inner}} = \frac{D_{outer}}{D_{inner}} \times \frac{\sin(\arctan(\frac{\pi D_{inner}}{P_{inner}}))}{\sin(\arctan(\frac{\pi D_{outer}}{P_{outer}}))}
$$
\n(9)

Equation 9 is an expression of an ideal relationship between various factors that affect the net magnetic field  $B_{\parallel}^{NET}$  parallel to the direction  $\hat{z}$  of light propagation. When  $B_{\parallel}^{NET}$  parallel to the direction  $\hat{z}$  of light propagation. When <sup>25</sup><br>these factors (the diameter  $D_{inner}$  of the inner helix structure,<br>the pitch the diameter  $D_{outer}$  of the outer helix structure, the pitch<br> $p_{inner}$  of inner layer, and the current  $I_{outer}$ , flowing in the wires of the<br>possible because the wire strands comprise wire strands of<br>outer layer) satisfy the relationship of Equation 9, then the<br>different electrical conductivity. net magnetic field  $B_{\parallel}^{NET}$  parallel to the direction  $\hat{z}$  of light This is evident from a comparison of a conventional propagation is minimized. OPGW cable having all of the strands of relatively high-

ratio of the combined resistivity of the strands of the inner<br>lalanced OPGW cable having equal numbers of strands of the strands of the outer<br>latively high-k wire in its inner layer and its outer layer. layer. Most of the contribution to the currents comes from<br>the strands of relatively high - k wire in cases where the **Example 1**) 2-Layer Conventional 30-Strand the strands of relatively high- $\kappa$  wire, in cases where the Example 1) 2-Layer Conventing electrical conductivity of the relatively high- $\kappa$  wire is sig- 40 electrical conductivity of the relatively high- $\kappa$  wire is sig- $40$ nificantly greater than the electrical conductivity of the relatively low- $\kappa$  wire. For example, aluminum is about 22  $\mu$  relatively low-k wire. For example, aluminum is about 22<br>relatively low-k wire. For example, aluminum is about 22<br>referred to in this document as "the example 2-layer con-<br>ratio I (I) of the currents can be controlle ratio  $I_{\text{outer}}/I_{\text{inner}}$  of the currents can be controlled (on a coarse ventional 30-strand OPGW cable  $\%$ , is illustrated in F1 scale) by determining how many strands of relatively high- $\kappa$  45 (PRIOR ART) and meets the scale) by determining how many strands of relatively high- $\kappa$  45 (PRIOR ART) and meets the following specifications in the outer layer versus the inner layer. The actual  $\frac{30 \text{ strands of wire, all same wire gauge}}{30 \text{stands of wire}}$ wire are in the outer layer versus the inner layer. The actual  $\frac{30 \text{ strands of wire}}{30 \text{ ster}}$ , all same wire gauge<br>ratio I A of the currents can be further controlled (on Outer layer: 18 strands of aluminum, diameter  $D_{outer}$ ratio  $I_{outer}/I_{inner}$  of the currents can be further controlled (on Outer layer: 18 strands of alu a finer scale) by determining the number of strands of the  $0.016$  m, pitch  $p_{outer}=0.2$  m a finer scale) by determining the number of strands of the  $0.016$  m, pitch  $p_{outer} = 0.2$  m relatively low-k wire in the outer layer versus the inner layer 12 strands of steel, diameter  $D_{inner} = 0.011$  m, layer. The total number of strands of relatively high- $\kappa$  wire in the pinner  $\frac{1}{2}$  pitch  $p_{inner} = 0.2$  m and of strands of relatively low  $\kappa$  wire is also subject to pitch PIG. 9 (PRIOR ART) shows a cross-section of and of strands of relatively low- $\kappa$  wire is also subject to FIG 9 (PRIOR ART) shows a cross-section of an example<br>electrical conductivity and mechanical/tensile strength engi- OPGW cable 900. The cable 900 is construct

determined by the gauge of the wire used and by the strands are located in the outer layer 908. No aluminum diameter of the core element and therefore are not easily strands are located in the inner layer 906. diameter of the core element and therefore are not easily strands are located in the inner layer **906**.<br>
controlled One can consider the diameters to be predeter-<br>
The actual ratio  $I_{outer}/I_{inner}$  of the currents in the cable controlled. One can consider the diameters to be predeter-<br>mined.

The pitch  $p_{inner}$  of the inner helix structure and the pitch 60  $p_{outer}$  of the outer helix structure should be manufacturing variables that can be customized, within reason, allowing some fine tuning of the net magnetic field  $B_{\parallel}^{NET}$  parallel to the direction  $\hat{z}$  of light propagation.

Ideal Current Ratio  $18 \times 2.8 \times 10^{-5}$ <br>For fixed values of the diameters and the pitches, Equation 9 is an expression of an ideal ratio of currents ("ideal

10

layer 106.<br>Ideally, the outer magnetic field  $B_{outer}$  is equal to the inner ment achieve, for a 2-layer OPGW cable, that an actual ratio percent of an ideal ratio of the outer current  $I_{outer}$  to the inner current  $I_{inner}$ , where the actual ratio is calculated as a ratio of combined resistivity of the strands of the inner layer to  $\frac{10}{10}$  combined resistivity of the strands of the outer layer, and the ideal ratio is calculated per Equation 9.

For an OPGW cable having outer diameter  $D_{outer} = 0.016$  m, outer pitch  $p_{outer} = 0.2$  m, inner diameter  $D_{inner} = 0.011$  m, which can be simplified and rearranged as Equation 9:  $\frac{15}{15}$  and inner pitch  $p_{inner} = 0.2$  m, the ideal current ratio can be calculated by substituting the numerical values of the diam eters and the pitches into Equation 9, yielding the approximate ideal current ratio 1.016 as shown in Equation 10:

$$
\left(\frac{I_{outer}}{I_{inner}}\right)^{IDEAL} = 1.\overline{45} \times \frac{\sin\left(\arctan\left(\frac{\pi}{18.18}\right)\right)}{\sin\left(\arctan\left(\frac{\pi}{12.5}\right)\right)} \approx 1.016\tag{10}
$$

opagation is minimized.<br>The actual ratio  $I_{\text{outer}}/I_{\text{inner}}$  of the currents is given by the  $_{35}$  wire in its outer layer to a proposed 2-layer roughly-

electrical conductivity and mechanical/tensile strength engi-<br>neering requirements for the OPGW cable.<br>The diameter D of the inner helix structure and the inner layer 906 composed of 12 steel strands, and an outer The diameter  $D_{inner}$  of the inner helix structure and the inner layer 906 composed of 12 steel strands, and an outer diameter  $D_{outer}$  of the outer helix structure are largely 55 layer 908 composed of 18 aluminum strands. Al

can be calculated as follows:

$$
\left(\frac{I_{outer}}{I_{inner}}\right)^{ACTUAL} = \frac{\text{combined resistivity of 12 steel strands}}{\text{combined resistivity of 18 Al strands}} = \frac{(11)\times 6.3 \times 10^{-7}}{1.2 \times 6.3 \times 10^{-7}} = \frac{756}{50.4} = 15
$$

65

far larger than the approximate ideal current ratio  $1.016$ .

Example 2) 2-Layer Roughly-Balanced 30-Strand<br>OPGW Cable

A specific example of the roughly-balanced OPGW cable, combined resistivity of 9 Al strands and 3 steel strands referred to in this document as "the example 2-layer combined resistivity of 9 Al strands and 6 steel strands roughly-balanced 30-strand OPGW cable", meets the following specifications:

30 strands of wire , all same wire gauge 12 strands of steel required for tensile strength

Figure 1000. The cable 1000 is constructed of a core element<br>1002 that carries one or more optical fibers 1004, an inner . Example 4) 2-Layer Pitch-Adjusted 1002 that carries one or more optical fibers 1004, an inner  $\frac{1002 \text{ thm}}{20}$  Example 4) 2-Layer Pitch-Adjusted layer 1006 composed of 3 steel strands and 0 aluminum layer 1006 composed of 3 steel strands and 9 aluminum strands , and an outer layer 1008 composed of 9 steel strands and 9 aluminum strands. An equal number of aluminum and a specific example of the pitch-adjusted roughly-bal-<br>strands are located in the inner layer 1006 and in the outer anced OPGW cable, referred to in this document as "

The actual ratio  $I_{outer}/I_{inner}$  of the currents in the cable  $\begin{array}{c}\n0.1 \text{ or } 0.000 \text{ cm} \\
30 \text{ strands of wire, all same wire gauge} \\
1000 \text{ can be calculated as follows:}\n\end{array}$ 

$$
\left(\frac{I_{outer}}{I_{inner}}\right)^{ACTUAL} = \tag{12}
$$

$$
\frac{0.307 \times 10^{-8}}{0.297 \times 10^{-8}} = \frac{30.7}{29.7} = 1.034
$$

35

45

to the outer layer 1008, the actual ratio  $I_{outer}/I_{inner}$  of the 40 currents becomes close to the "ideal current ratio" (in this case, within about 2% of the approximate ideal current ratio case, within about 2% of the approximate ideal current ratio  $\left(\frac{I_{outer}}{I_{inner}}\right)^{Dect} = 1.45 \times \frac{(17.8636)^{7}}{\sin\left(\arctan\left(\frac{\pi}{12.5}\right)\right)} \approx 1.0336$ 

## Example 3) 2-Layer Low-K Adjusted

A specific example of the low-k adjusted roughly-bal-<br>anced OPGW cable, referred to in this document as "the<br>example 2-layer roughly-balanced 27-strand OPGW cable", 50<br>meets the following specifications:<br>The appropriate i

diameter  $D_{outer}$ =0.016 m, pitch  $p_{outer}$ =0.2 m 55<br>Inner layer: 9 strands of aluminum, 3 strands of steel,<br>diameter  $D_{inner}$ =0.011 m, pitch  $p_{inner}$ =0.2 m

FIG. 11 shows a cross-section of an example cable 1100.<br>The cable 1100 is constructed of a core element 1102 that<br>carries one or more optical fibers 1104, an inner layer 1106 60 and then substituting the numerical values o carries one or more optical fibers 1104, an inner layer 1106  $60$  composed of 3 steel strands and 9 aluminum strands, and an composed of 3 steel strands and 9 aluminum strands, and an eters, the outer pitch  $p_{outer}$ , and the actual ratio  $I_{outer}/I_{inner}$  of outer layer 1108 composed of 6 steel strands and 9 alumi-<br>the currents (calculated as the ratio

The cable 1100 differs from the cable 1000 (Example 2)  $65$  in that the cable 1100 has 3 fewer strands of steel in its outer in that the cable 1100 has 3 fewer strands of steel in its outer considered fixed, and the appropriate outer pitch that makes layer 1108.

Clearly the actual ratio of the currents in the cable 900 is The actual ratio  $I_{outer}/I_{inner}$  of the currents in the cable r larger than the approximate ideal current ratio 1.016. 1100 can be calculated as follows:

OPGW Cable 
$$
\left(\frac{I_{outer}}{I_{inner}}\right)^{ACTUAL} =
$$
 (13)

 $\frac{0.307 \times 10^{-8}}{0.302 \times 10^{-8}} = \frac{30.7}{30.2} = 1.0166$ 

Outer layer: 9 strands of aluminum, 9 strands of steel, What Equation 13 demonstrates is that by allocating equal diameter D = 0.016 m nitch n = 0.2 m diameter  $D_{outer} = 0.016$  m, pitch  $p_{outer} = 0.2$  m numbers of aluminum strands to the inner layer 1106 and to the inner layer 1106 and to the inner layer 1106 and to the inner layer 9 strands of aluminum 3 strands of steel  $10$ Inner layer: 9 strands of aluminum, 3 strands of steel, <sup>13</sup> the outer layer 1108, and by having fewer steel strands from<br>diameter D =0.011 m nitch n =0.2 m the outer layer 1108, the actual ratio  $I_{outer}/I_{inner}$  of the diameter  $D_{inner} = 0.011$  m, pitch  $p_{inner} = 0.2$  m the outer layer 1108, the actual ratio  $I_{outer} I_{inner}$  of the  $Y_{inner} = 0.2$  flow the value of an example OPGW currents becomes very close to the "ideal current ratio".

anced OPGW cable 2-layer pitch-adjusted roughly-balanced 30-strand<br>layer 1008 and in the strands are located in the inner layer 1006 and in the outer example 2-layer pitch-adjusted roughly-balanced 30-strand  $^{25}$  OPGW c

12 strands of steel required for tensile strength<br>Outer layer: 9 strands of aluminum, 9 strands of steel,

diameter  $D_{outer} = 0.016$  m, pitch  $p_{outer} = 0.2$  m

 $^{30}$  Unanicic  $D_{outer}$ -0.010 in, picn  $p_{outer}$ -0.2 in<br>Inner layer: 9 strands of aluminum, 3 strands of steel,

 $\frac{1}{2}$ <br>  $\frac{1}{2}$ <br> roughly-balanced 30-strand OPGW cable (Example 3) in that the inner pitch has been shortened by 3.5 mm. Substituting the numerical values of the diameters and the pitches What Equation 12 demonstrates is that by allocating equal into Equation 9 yields a revised approximate ideal current numbers of the aluminum strands to the inner layer 1006 and

$$
\left(\frac{I_{outer}}{I_{inner}}\right)^{IDEAL} = 1.\overline{45} \times \frac{\sin\left(\arctan\left(\frac{\pi}{17.8636}\right)\right)}{\sin\left(\arctan\left(\frac{\pi}{12.5}\right)\right)} \approx 1.0336\tag{14}
$$

Roughly-Balanced 27-Strand OPGW Cable<br>What Equation 14 demonstrates is that by selecting an<br>appropriate inner pitch, the "ideal current ratio" can be made

Example of wire, all same wire gauge<br>
27 strands of wire, all same wire gauge<br>
9 strands of steel required for tensile strength<br>
9 strands of steel required for tensile strength<br>
Outer layer: 9 strands of aluminum, 6 stra

$$
p_{inner} = \frac{\pi D_{inner}}{\tan\left(\arcsin\left[\frac{D_{inner}}{D_{outer}} \times \left(\frac{I_{outer}}{I_{inner}}\right)^{ACTUAL} \times \sin\left(\arctan\left(\frac{\pi D_{outer}}{p_{outer}}\right)\right)\right]\right)}
$$
(15)

the currents (calculated as the ratio of the combined resisnum strands. An equal number of aluminum strands are tivity of the strands of the inner layer to the combined located in the inner layer 1106 and in the outer layer 1108. resistivity of the strands of the outer layer). located in the inner layer 1106 and in the outer layer 1108. resistivity of the strands of the outer layer).<br>The cable 1100 differs from the cable 1000 (Example 2) 65 In an alternative implementation, the inner pitch may b

the "ideal current ratio" nearly identical to the actual ratio

 $T_{outer}/T_{inner}$  of the currents can be calculated isolating the reversed lay direction stranding", is illustrated in FIG. 13 outer pitch  $p_{outer}$  in Equation 9 to arrive at Equation 16: and meets the following specifications: outer pitch  $p_{outer}$  in Equation 9 to arrive at Equation 16:

$$
p_{outer} = \frac{\pi D_{outer}}{\tan\left(\arcsin\left(\frac{D_{inner}}{D_{inner}}\right)\right)} \left(\frac{D_{outer}}{D_{inner}}\times\sin\left(\arctan\left(\frac{\pi D_{inner}}{D_{inner}}\right)\right)\right)}
$$
(16) 5

and then substituting the numerical values of the diameters, Layer 3 (stranded in a right-hand, CW direction): 24<br>the inner pitch  $p_{inner}$  and the actual ratio  $I_{outer}/I_{inner}$  of the strands of aluminum, diameter  $D_3$ =0.021 m, the inner pitch  $p_{inner}$ , and the actual ratio  $I_{outer}/I_{inner}$  of the strands of currents (calculated as the ratio of the combined resistivity  $p_3=0.2 \text{ m}$ currents (calculated as the ratio of the combined resistivity of the strands of the inner layer to the combined resistivity  $_{15}$  Layer 4 (stranded in a left-hand, CCW lay direction): 30 of the strands of the outer layer).

These concepts will now be demonstrated with specific examples of 4-layer OPGW cables, such as illustrated in with alternately reversed lay direction stranding. The cable FIG.  $\bf{5}$  and FIG.  $\bf{6}$ .

- 
- strands of steel, diameter  $D_1 = 0.011$  m, pitch  $p_1 = 0.2$  m tion (Layer 2 (stranded in a left-hand, CCW lay direction): 18 4).
- Layer 3 (stranded in a right-hand, CW direction): 24  $35$  strands of aluminum, diameter  $D_3=0.021$  m, pitch
- 

The cable 1200 is constructed of a core element 1202 that would flow in each layer is based on the inverse ratio of a carries one or more optical fibers 1204, a first layer 1206 given layer's resistivity to the total resis carries one or more optical fibers 1204, a first layer 1206 given layer's resistivity to the total resistivity of the OPGW composed of 12 steel strands, a second layer 1208 composed cable 1300. of 18 aluminum strands, a third layer 1210 composed of 24 45 aluminum strands, and a fourth layer 1212 composed of 30 aluminum strands. No aluminum strands are located in the Example 7) 4-Layer Pitch-Adjusted innermost first layer 1206.

combined resistivity of 12 steel strands. The resistivity of the 50 second layer 1208 is given by the combined resistivity of 18 Al strands. The resistivity of the third layer 1210 is given by A specific example of a pitch-adjusted roughly-balanced the combined resistivity of 24 Al strands. The resistivity of OPGW cable, referred to in this document the fourth layer 1212 is given by the combined resistivity of 4-layer pitch-adjusted roughly-balanced 84-strand OPGW 30 Al strands. The total resistivity of the OPGW cable 1200 55 cable with alternately reversed lay direction stranding", is the resistivity of all layers combined in parallel. The meets the following specifications:<br>
84 st proportion of the current that would flow in each layer is 84 strands of wire, all same wire gauge based on the inverse ratio of a given layer's resistivity to the 12 strands of steel required for tensile strength

# Example 6) 4-Layer Roughly-Balanced 84-Strand<br>
OPGW Cable with Alternately Reversed Lay Layer 2 (stranded in a left-hand, CCW lay direction): 6

A specific example of a roughly-balanced OPGW cable,  $\frac{65}{100}$  Layer 3 (stranded in a left-hand, CW direction): 24 referred to in this document as "the example 4-layer strands of aluminum, diameter  $D_3 = 0.021$  m, pitc roughly-balanced 84-strand OPGW cable with alternately  $p_3 = 0.2 \text{ m}$ 

84 strands of wire, all same wire gauge<br>12 strands of steel required for tensile strength

- Layer 1 (stranded in a right-hand, CW direction):  $12$ strands of aluminum, diameter  $D_1 = 0.011$  m, pitch  $p_1 = 0.2$  m
- Layer 2 (stranded in a left-hand, CCW lay direction): 6 strands of aluminum, 12 strands of steel, diameter  $s = 0.016$  m, pitch  $p_2 = 0.2$  m<br>Layer 3 (stranded in a right-hand, CW direction): 24
	-
- Specific Examples for 4-Layer OPGW Cables  $p_4 = 0.2 \text{ m}$ <br>These concepts will now be demonstrated with specific FIG. 13 shows a cross-section of an example cable 1300

20 1300 is constructed of a core element 1302 that carries one<br>or more optical fibers 1304, a first layer 1306 composed of Example 5) 4-Layer 84-Strand OPGW Cable 12 aluminum strands, a second layer 1308 composed of 6 aluminum strands and 12 steel strands, a third layer 1310 A specific example of an OPGW cable, referred to in this<br>document as "the example 4-layer 84-strand OPGW cable", and a fourth layer 1310<br>is illustrated in FIG. 12 and meets the following specifica-<br>is illustrated in FIG.  $\frac{1}{2}$  and 24 Al strands from Layer 3) is equal to the number of  $\frac{1}{2}$  strands from Layer 3 is equal to the number of  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  aluminum wires stranded in the left-hand, CCW lay directio Layer 1 (stranded in a right-hand, CW direction): 12 30 aluminum wires stranded in the left-hand, CCW lay directions strands of steel diameter  $D = 0.011 \text{ m}$  pitch  $n = 0.2 \text{ m}$  tion (6 Al strands from Layer 2 and 30 Al

strands of aluminum, diameter  $D_2$ =0.016 m, pitch The resistivity of the first layer 1306 is given by the combined resistivity of 12 Al strands. The resistivity of the combined resistivity of 12 Al strands. The resistivity of the second layer  $1308$  is given by the combined resistivity of 6 strands of aluminum, diameter  $D_3=0.021$  m, pitch Al strands and 12 steel strands. The resistivity of the third<br>hym-0.2 m<br>Al strands and 12 steel strands. The resistivity of 24 Al  $p_3 = 0.2$  m layer 1310 is given by the combined resistivity of 24 Al Layer 4 (stranded in a left-hand, CCW lay direction): 30 strands. The resistivity of the fourth layer 1312 is given by strands. The resistivity of the fourth layer 1312 is given by the combined resistivity of 30 Al strands. The total resistivstrands of aluminum, diameter  $D_4=0.026$  m, pitch the combined resistivity of 30 Al strands. The total resistivity of all layers  $p_4=0.2$  m FIG. 12 shows a cross-section of an example cable 1200. combined in parallel. The proportion of the current that

# incompost first layer 1206.<br>
The resistivity of the first layer 1206 is given by the Alternately Reversed Lay Direction Stranding

- 
- 
- based on the inverse ratio of a given layer's resistivity to the 12 strands of steel required for tensile strength total resistivity of the OPGW cable 1200.<br>
Layer 1 (stranded in a right-hand, CW direction): 12<br>  $\frac{60}{10$ 
	- Direction Stranding Strands of aluminum, 12 strands of steel, diameter  $D_2=0.016$  m, pitch  $p_2=0.2$  m<br>Layer 3 (stranded in a left-hand, CW direction): 24
		-

Layer 4 (stranded in a right-hand, CCW lay direction): 30 83 strands of wire, all same wire gauge<br>strands of aluminum, diameter 11 strands of steel required for tensile strength<br> $D_4=0.026$  m, pitch  $p_4=0.2$  m  $D_5=1$  (s

10 The example 4-layer pitch-adjusted roughly-balanced strands of aluminum, 6 strand OPGW cable with alternately reversed lay direc-  $5 \text{ } D_1 = 0.011 \text{ m}$ , pitch  $p_1 = 0.2 \text{ m}$ 84-strand OPGW cable with alternately reversed lay direc-<br>tion stranding differs from the 4-layer roughly-balanced<br>Layer 2 (stranded in a left-hand, CCW lay direction): 12 tion stranding differs from the 4-layer roughly-balanced Layer 2 (stranded in a left-hand, CCW lay direction): 12<br>84-strand OPGW cable (Example 6) with alternately strands of aluminum, 5 strands of steel, diameter 84-strand OPGW cable (Example 6) with alternately strands of aluminum, 5 strands of aluminum, 5 str<br>reversed lay direction stranding in that nitch of layer 1 has  $D_2=0.016$  m, pitch  $p_2=0.2$  m reversed lay direction stranding in that pitch of layer 1 has been lengthened by 10 mm.

## Example 8) 4-Layer Roughly-Balanced 84-Strand OPGW Cable

Another specific example of a roughly-balanced OPGW  $p_4=0.2 \text{ m}$ <br>cable, referred to in this document as "the example 4-layer"  $p_4 = 0.15 \text{ m}$  and  $p_5 = 0.15 \text{ m}$  and  $p_6 = 0.15 \text{ m}$ 

- 
- 
- strands of aluminum, diameter  $D_3=0.021$  m, pitch differs from the cable 1400 in that the cable 1500 strand of steel in its innermost first layer 1506.
- 

The cable 1400 is constructed of a core element 1402 that of the third layer 1510 is given by the combined resistivity or more ortical fibers 1404 a first layer 1406  $^{35}$  of 24 Al strands. The resistivity of the fourth carries one or more optical fibers 1404, a first layer 1406  $\frac{35}{124}$  Al strands. The resistivity of 30 Al strands. The total composed of 6 aluminum strands and 6 steel strands, a given by the combined resistivity of 3 second layer 1408 composed of 12 aluminum strands and 6<br>second layer 1408 composed of 12 aluminum strands and 6<br>second layer 1410 composed of 24 aluminum<br>trands and 6<br>strands, a third layer 1410 composed of 24 aluminum<br>th strands. The cable is "roughly balanced" in that the number<br>of aluminum wires stranded in the right-hand, CW lay<br>direction (6 Al strands from Layer 1 and 30 Al strands from Example 10) 4-Layer Low-K Adjusted<br>Layer 4) is eq in the left-hand, CCW lay direction  $(12 \text{ Al strands from } 45 \text{ Layer } 2 \text{ and } 24 \text{ Al strands from Layer } 3)$ . second layer 1408 composed of 12 aluminum strands and 6

The resistivity of the first layer 1406 is given by the A specific example of a low-k adjusted pitch-adjusted<br>combined resistivity of 6 Al strands and 6 steel strands. The roughly-balanced OPGW cable, referred to in this d resistivity of 12 Al strands and 6 steel strands. The resistivity 50 roughly-balanced 83-s of the third layer 1410 is given by the combined resistivity lowing specifications: of the third layer 1410 is given by the combined resistivity lowing specifications:<br>of 24 Al strands. The resistivity of the fourth layer  $1412$  is 83 strands of wire, all same wire gauge given by the combined resistivity of 30 Al strands. The total 11 strands of steel required for tensile strength<br>resistivity of the OPGW cable 1400 is the resistivity of all Layer 1 (stranded in a right-hand, CW direction): layers combined in parallel. The proportion of the current 55 strands of aluminum, 6 strands of strands of strands of strands of strands of strands of step, =0.180 m that would flow in each layer is based on the inverse ratio of  $D_1=0.011$  m, pitch  $p_1=0.180$  m<br>a given layer's resistivity to the total resistivity of the Layer 2 (stranded in a left-hand, CCW lay direction): 12 a given layer's resistivity to the total resistivity of the OPGW cable 1400.

A specific example of a low-k adjusted roughly-balanced Layer 4 (stranded in a right-hand, CW lay direction): 30<br>OPGW cable, referred to in this document as "the example strands of aluminum, diameter  $D_4$ =0.026 m, pitch 4-layer low-k adjusted roughly-balanced 83-strand OPGW 65  $p_4=0.2 \text{ m}$ <br>cable", is illustrated in FIG. 15 and meets the following The example 4-layer low-k adjusted pitch-adjusted specifications: The following the following The following The example 4 - layer low - adjusted pitch - adjusted pitch - adjusted pitch - adjusted specifications : roughly - balanced 83-strand OPGW cable differs from the

- 
- 
- Layer 1 (stranded in a right-hand, CW direction): 6 strands of aluminum, 6 strands of steel, diameter
- 
- Layer 3 (stranded in a left-hand, CCW direction): 24 strands of aluminum, diameter  $D_3=0.021$  m, pitch  $p_3=0.2$  m
- Layer 4 (stranded in a right-hand, CW lay direction): 30 strands of aluminum, diameter  $D_4=0.026$  m, pitch  $p_4=0.2$  m

cable, referred to in this document as "the example 4-layer" and the strands of steel roughly-balanced 84-strand OPGW cable", is illustrated in<br>
FIG. 15 shows a cross-section of an example cable 1500.<br>
The cable 1500 is co  $D_1=0.011$  m, pitch  $p_1=0.2$  m of aluminum wires stranded in the right-hand, CW lay Layer 2 (stranded in a left-hand, CCW lay direction): 12 direction (6 A1 strands from Layer 1 and 30 A1 strands from layer 2 (stranded in a left-hand, CCW lay direction): 12 direction (6 Al strands from Layer 1 and 30 Al strands from<br>strands of aluminum, 6 strands of steel, diameter 25 Layer 4) is equal to the number of aluminum wires st strands of aluminum, 6 strands of steel, diameter 25 Layer 4) is equal to the number of aluminum wires stranded<br> $D_2=0.016$  m, pitch  $p_2=0.2$  m in the left-hand, CCW lay direction (12 Al strands from  $D_2=0.016$  m, pitch p<sub>2</sub>=0.2 m in the left-hand, CCW lay direction (12 Al strands from Layer 3 (stranded in a left-hand, CCW direction): 24 Layer 2 and 24 Al strands from Layer 3). The cable 1500 Layer 2 and 24 Al strands from Layer 3). The cable  $1500$  differs from the cable  $1400$  in that the cable  $1500$  has 1 fewer

Layer 4 (stranded in a right-hand, CW lay direction):  $30<sup>30</sup>$  The resistivity of the first layer 1506 is given by the strands of aluminum, diameter combined resistivity of 6 Al strands and 6 steel strands. The resistivity of the second layer 1508 is given by the combined  $D_4 = 0.026$  m, pitch  $p_4 = 0.2$  m resistivity of the second layer 1508 is given by the combined resistivity of 12 Al strands and 5 steel strands. The resistivity FIG. 14 shows a cross-section of an example cable 1400. resistivity of 12 Al strands and 5 steel strands. The resistivity of the third layer 1510 is given by the combined resistivity of the third layer 1510 is given by th

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- strands of aluminum, 5 strands of steel, diameter D<sub>2</sub>=0.016 m, pitch  $p_2$ =0.2 m
- Example 9) 4-Layer Low-K Adjusted 60 Layer 3 (stranded in a left-hand, CCW direction): 24<br>Roughly-Balanced 83-Strand OPGW Cable strands of aluminum, diameter D<sub>3</sub>=0.021 m, pitch Roughly-Balanced 83-Strand OPGW Cable strands of aluminum, diameter  $D_3 = 0.021$  m, pitch<br>  $p_3 = 0.2$  m<br>
A specific example of a low-k adjusted roughly-balanced Layer 4 (stranded in a right-hand, CW lay direction): 30
	-

cable (Example 9) in that pitch of layer 1 has been shortened cause a rate of change of SOP of 33 rad/s, which is virtually<br>by 20 mm.<br>In the example 4-layer roughly-balanced 84-strand<br>In the example 4-layer roughly-balance

Lightning Strikes and Rate of Change of SOP<br>Now consider a lightning strike on these example cables. being shunted to Earth ground by a tower. Equation / can be<br>used to calculate the rate of change of SOP.<br>A typical lightning strike has a transition time of 5 usec<br>A typical lightning strike has a transition time of 5 usec

A typical lightning strike has a transition time of 5 µsec<br>and OPGW cable (Example 9), that typical lightning<br>and induces a current of 30 kA. In the example 2-layer <sup>10</sup> strike will cause a rate of change of SOP of 19.8 k typical lightning strike will cause a rate of change of SOP of able coherent technologies.<br>
1.98 Mrad/s, which is difficult for currently available cohereived and the example 4-layer low-K adjusted pitch-adjusted<br>
ent tech layer reduces the rate of change of SOP resulting from a extreme lightning strike will cause a rate of change of SOP typical lightning strike by over 2 orders of magnitude. of 32.9 Mrad/s, which is far beyond the tracking

OPGW cable (Example 3), that typical lightning strike will example 2-layer roughly-balanced 30-strand OPGW cable<br>cause a rate of change of SOP of 550 rad/s, which is well 25. (Example 2), that extreme lightning strike wil cause a rate of change of SOP of 550 rad/s, which is well  $^{25}$  (Example 2), that extreme lightning strike will cause a rate<br>within the tracking ability of currently available coherent<br>tracking strike will be constructed

30-strand OPGW cable (Example 4), that typical lightning  $\frac{30}{2}$  the outer layer, the rate of change of SOP resulting from an strike will cause a rate of change of SOP of 390 rad/s, which  $\frac{30}{2}$  extreme lightning s strike will cause a rate of change of SOP of 390 rad/s, which <sup>30</sup> extreme lightning strike is reduced to a trackable amount.<br>is well within the tracking ability of currently available <br>operation of the example 2-layer rou

5), that typical lightning strike will cause a rate of change of within the tracking ability of currently available coherent SOP of 621 krad/s, which is beyond the capability for some  $35$  technologies. available coherent technologies to track. In contrast, in the In the example 2-layer pitch-adjusted roughly-balanced 84-strand OPGW cable 30-strand OPGW cable (Example 4), that extreme lightning with alternately reversed lay direction stranding (Example strike will cause a rate of change of SOP of 6.5 krad/s, which 6), that typical lightning strike will cause a rate of change of  $\frac{1}{10}$  is well within the trac 6), that typical lightning strike will cause a rate of change of is well within the tracking ability of currently available SOP of 15.5 krad/s, which is well within the tracking ability  $40$  coherent technologies. Thus pi

84-strand OPGW cable with alternately reversed lay direc-<br>These calculations are summarized in Table 1:

18

4-layer low- $\kappa$  adjusted roughly-balanced 83-strand OPGW tion stranding (Example 7), that typical lightning strike will cable (Example 9) in that pitch of layer 1 has been shortened cause a rate of change of SOP of 33 ra

OPGW cable (Example 8), that typical lightning strike will cause a rate of change of SOP of 20.9 krad/s, which is within that causes current to travel along 100 m of the cable before<br>being capability of currently available coherent tech-<br>het travel in that causes a rate of currently available coherent tech-<br>hetaxing capability of currently a

typical lightning strike by over 2 orders of magnitude. of 32.9 Mrad/s, which is far beyond the tracking ability of<br>In the example 2-layer roughly-balanced 27-strand currently available coherent technologies. In contrast, In the example 2-layer roughly-balanced 27-strand currently available coherent technologies. In contrast, in the<br>PGW cable (Example 3), that typical lightning strike will example 2-layer roughly-balanced 30-strand OPGW cab Fracking ability of many currently available coherent technologies.<br>
In the example 2-layer pitch-adjusted roughly-balanced<br>
30-strand OPGW cable (Example 4), that typical lightning<br>
the outer layer the rate of change of S

herent technologies.<br>In the example 4-layer 84-strand OPGW cable (Example cause a rate of change of SOP of 8.4 krad/s, which is well In the example 4-layer 84-strand OPGW cable (Example cause a rate of change of SOP of 8.4 krad/s, which is well 5), that typical lightning strike will cause a rate of change of  $\sim$  within the tracking ability of currently

SOP of 15 . 5 krad / s , which is well within the tracking ability coherent technologies . Thus pitch - adjusted roughly - bal currently available coherent technologies. <br>In the example 4-layer pitch-adjusted roughly-balanced even extreme lightning strikes.

TABLE 1

Example	Rate of Change of SOP due to Typical Lightning Strike	Rate of Change of SOP due to Extreme Lightning Strike
1) Conventional 2-layer 30-strand OPGW cable	$1.98$ Mrad/s	$32.9$ Mrad/s
2) 2-layer roughly-balanced 30-strand OPGW cable	$17.5$ krad/s	$292$ krad/s
3) 2-layer low-K adjusted roughly-balanced 27-strand OPGW cable	$550$ rad/s	$8.4$ krad/s
4) 2-layer pitch-adjusted roughly-balanced 30-strand OPGW cable	$390$ rad/s	$6.5$ krad/s
5) 4-layer 84-strand OPGW cable	$621$ krad/s	$10.3$ Mrad/s
6) 4-layer roughly-balanced 84-strand OPGW cable with alternately reversed lay direction stranding	$15.5$ krad/s	$259$ krad/s
7) 4-layer pitch-adjusted roughly-balanced 84-strand OPGW cable with alternately reversed lay direction stranding	$33 \text{ rad/s}$	545 rad/s
8) 4-layer roughly-balanced 84-strand OPGW cable	$20.9$ krad/s	$349$ krad/s
9) 4-layer low-K adjusted roughly-balanced 83-strand OPGW cable	$19.8$ krad/s	331 krad/s
10) 4-layer low-κ adjusted pitch-adjusted roughly- balanced 83-strand OPGW cable	$1.1$ krad/s	$19.1 \text{ rad/s}$

- 
- in the remaining (N-M ) layers, where M is an integer,<br>
M is less than N, and M21, and  $\frac{15}{10}$ . An optical ground wire (OPGW) cable comprising:<br>
wherein a total number of strands of the higher electrical<br>
a core eleme
- herein a total number of strands of the higher electrical a core element carrying one or more optical fibers;<br>conductivity wire in the M layers whose wires are an inner layer of concentric stranded wires stranded in an equal to a total number of strands of the higher elec-<br>trical conductivity wire in the remaining (N–M) layers 20  $D_{inner}$  and by an inner pitch  $p_{inner}$ ; and trical conductivity wire in the remaining  $(N-M)$  layers 20  $D_{inner}$  and by an inner pitch  $p_{inner}$ ; and whose wires are stranded in the left-hand, counter-<br>an outer layer of concentric stranded wires stranded in an

whose wires are stranded in the feri-hand, counter-<br>
an outer layer of concentric stranded wires stranded in an<br>
clockwise lay direction.<br>
2. The OPGW cable as recited in claim 1, wherein the<br>
higher electrical conductivi

lower electrical conductivity wire comprises steel or alumi-<br>num-clad steel. in the other layers, and 25

4. The OPGW cable as recited in claim 1, wherein N is 4. The OPGW cable as recited in claim 1, wherein N is wherein an actual ratio of an outer current  $I_{outer}$  in the equal to 2, M is equal to 1, the wires of an inner layer are wires of the outer layer to an inner current L i equal to 2, M is equal to 1, the wires of an inner layer are wires of the outer layer to an inner current  $I_{inner}$  in the stranded in an inner helix structure characterized by an inner  $\frac{30}{100}$  wires of the inner layer 30

layer to an inner current  $I_{inner}$  in the wires of the inner layer is within 10 percent of an ideal ratio of the outer current  $I_{outer}$  to the inner current  $I_{inner}$ , the actual ratio calculated as a ratio of combined resistivity of the strands of the inner  $^{40}$ layer to combined resistivity of the strands of the outer layer, and the ideal ratio calculated as:

$$
\Big(\frac{I_{outer}}{I_{inner}}\Big)^{IDEAL} = \frac{D_{outer}}{D_{inner}} \times \frac{\sin\Big(\arctan\Big(\frac{\pi D_{inner}}{P_{inner}}\Big)\Big)}{\sin\Big(\arctan\Big(\frac{\pi D_{outer}}{P_{outer}}\Big)\Big)}.
$$

 $19$   $20$ 

The scope of the claims should not be limited by the 6. The OPGW cable as recited in claim 5, wherein the details set forth in the examples, but should be given the actual ratio is within 2 percent of the ideal ratio.

broadest interpretation consistent with the description as a<br>whole.<br>What is claimed is:<br>1. An optical ground wire (OPGW) cable comprising:<br>3. The OPGW cable as recited in claim 1, wherein N is<br>a core element carrying one o

a core element carrying one or more optical fibers;<br>
N layers of concentric stranded wires, where N is an equal to 4, M is equal to 2, and wires of an innermost layer N layers of concentric stranded wires, where N is and equal to 4, M is equal to 2, and wires of an innermost layer<br>integer and  $N\ge 2$ , the stranded wires comprising strands<br>of higher electrical conductivity wire and stra

- stranded in the right-hand, clockwise lay direction is an inner layer of concentric stranded wires stranded in an<br>equal to a total number of strands of the higher election inner helix structure characterized by an inner di
	-
- 3. The OPGW cable as recited in claim 1, wherein the  $\frac{25}{3}$  lay direction in one of the layers and the wires are  $\frac{25}{3}$ . The OPGW cable as recited in claim 1, wherein the stranded in a left-hand, counter-clockwise
- stranded in an inner neix structure characterized by an inner<br>diameter  $D_{inner}$  and by an inner pitch  $D_{inner}$  and the wires of the inner layer is within 10 percent of an ideal<br>ratio of the outer current  $D_{outer}$  to the inner c

$$
\frac{I_{outer}}{I_{inner}}\Big|^{DEAL} = \frac{D_{outer}}{D_{inner}} \times \frac{\sin(\arctan(\frac{\pi D_{inner}}{D_{inner}}))}{\sin(\arctan(\frac{\pi D_{outer}}{D_{outer}}))}.
$$

11. The OPGW cable as recited in claim 10, wherein the actual ratio is within 2 percent of the ideal ratio.

12. The OPGW cable as recited in claim 10, wherein a difference in a number of wires in the outer layer and a number of wires in the inner layer is not equal to 6.

\* \* \* \* \*