Guided Modes on Open Chirowaveguides

Samir F. Mahmoud

***Abstract*—Surface wave modes on an open chiral rod and a planar chiral slab are studied. It is shown that the effect of chirality is to split each mode in the nonchiral case to a pair of modes, the cutoff frequencies of which are above and below that of the nonchiral case. The mode with the lower cutoff frequency is dominantly right circularly polarized (RCP) mode while the mode with the higher cutoff frequency is dominantly left circularly polarized (LCP) mode near their respective cutoff frequencies. At sufficiently higher frequencies, all modes tend to become RCP (assuming a right handed chiral medium). Closed form expressions for modal cutoff frequencies on the planar chiral slab and chiral circular rod are derived. The surface wave modes are classified as HE and EH modes and a suitable definition for these mode types, that reduces to well known definitions in the nonchiral case, is proposed.**

I. Introduction

MUCH interest has been focussed on interaction of microwaves with chiral materials during the last one or two decades. As a result, several interesting phenomena have been observed and several applications have been suggested [1]–[6]. Guided waves have been studied on what has been termed as "chirowaveguides" with perfectly reflecting walls [7]–[11] and with constant impedance walls [12]. Thus, mode bifucation phenomenon and states of polarization of modes have been investigated. Some works on open chirowaveguides have also been presented; Pelet and Engheta [6] provided rigorous analysis on excitation of surface wave modes and radiation modes on chiral slabs or, chirostrips. Cory and Tamir [13] studied modes on a chiral circular rod by expanding the modal fields in terms of those of a similar achiral rod. The modal phase constants of the chiral rod are then obtained as the eigenvalues of a matrix that contains coupling coefficients between modes. This method, termed as the field expansion method, although limited to a small chiral admittance relative to the achiral wave admittance, is attractive for being numerically simple. Uslenghi considered guided waves on certain special cases of bianisotropic waveguides [14].

In this paper we study surface wave modes on simple open chirowaveguides; namely a circular chiral rod and a planar chiral slab embedded in an external isotropic medium as depicted in Fig. 1(a), (b). The emphasis is on mode identification and the study of their polarization and behavior of their cutoff frequencies as compared to the nonchiral case. The chiral material is assumed to have permittivity $\varepsilon(F/m)$, chiral admittance ζ(mho) and permeability μ. Thus, for time harmonic fields varying as $\exp(i\omega t)$, the constitutive relations for the chiral medium can take the following form [1]–[3]:

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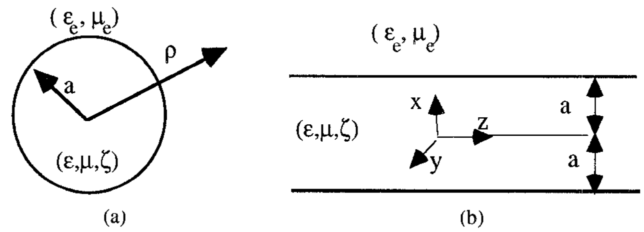

Fig. 1. Open Chirowaveguides: (a) A chiral rod. (b) A chiral slab.

$$\bar{D} = \varepsilon\bar{E} - i\zeta\bar{B} \tag{1}$$

$$\bar{H} = \bar{B}/\mu - i\zeta\bar{E} \tag{2}$$

with the usual meaning of the symbols. The chiral medium displays two bulk wavenumbers $k_\pm$ for right hand and left hand circularly polarized waves (RCP and LCP), respectively. These are given by [e.g. 12]:

$$k_\pm = k\Big[(1+c^2)^{1/2} \pm c\Big] \tag{3}$$

where $k = \omega(\mu\varepsilon)^{1/2}$ and $c = (\mu/\varepsilon)^{1/2}\zeta$, is a normalized chiral admittance relative to the achiral admittance $(\varepsilon/\mu)^{1/2}$. The external medium to the chiral rod or slab is homogeneous and isotropic with permeability μ_e and permittivity ε_e.

In Section II the modal equation for the surface wave modes on a chiral rod is derived using a rigorous approach. Study of the mode cutoff behavior and modal field polarization along with representative numerical examples are given in Section III. A similar study for the chiral slab is presented in Section IV and concluding remarks are given in Section V.

II. Modal Equation

Looking for natural modes on the chiral rod waveguide of Fig. 1(a), all fields for a given mode, are assumed to have the dependence $\exp(-i\beta z - in\phi)$ where β is the modal longitudinal wavenumber and n is a positive or negative integer specifiying the azimuthal field dependence. The vector fields in a chiral medium can be decomposed into right handed (with bulk wavenumber k_+) and left handed (with k_-) vector fields $\bar{R}$ and $\bar{L}$. Thus, the longitudinal fields E_z and H_z in the chiral rod may be written, apart from the common factor $\exp(-i\beta z - in\phi)$, as [11], [12]:

$$E_z = AR_z + BL_z = AJ_m(r\rho) + BJ_m(l\rho) \tag{4}$$

$$-i\eta_c H_z = AR_z - BL_z = AJ_m(r\rho) - BJ_m(l\rho) \tag{5}$$

where A and B are constants and $J_m(\cdot)$ is the Bessel function of first kind and of order $m = |n|$. The transverse wavenumbers r and l refer to right handed and left handed waves and are given by $(k_\pm^2 - \beta^2)^{1/2}$ respectively, while $\eta_c = [\mu/\varepsilon(l+c^2)]^{1/2}$ is the chiral wave impedance [11], [12].

The longitudinal field components in the external region $\rho \geq a$ are appropriately given, apart from the common factor $\exp(-i\beta z - in\phi)$, by

$$E_z = C_1 K_m(\alpha\rho) \tag{6}$$

$$-i\eta_e H_z = C_2 K_m(\alpha\rho) \tag{7}$$

where $K_m(\cdot)$ is the modified Bessel function of second kind and α is the transverse attenuation factor in air and is given by $(\beta^2 - k_e^2)^{1/2}$; $k_e = \omega(\mu_e\varepsilon_e)^{1/2}$ and $\eta_e = (\mu_e/\varepsilon_e)^{1/2}$.

Next one derives the azimuthal field components inside and outside the chiral rod from known formulas [e.g. 12], and imposes the four boundary conditions at $\rho = a$ requiring the continuity of E_z, E_φ, H_z and H_φ. After some manipulations to eliminate the constants C_1 and C_2, we get:

$$[M]_{2\times 2}\begin{bmatrix} A \\ B \end{bmatrix} = 0 \tag{8}$$

where $[M]_{2\times 2}$ is a 2×2 matrix whose elements are given by:

$$\begin{aligned} M_{11} &= -p_r(\beta) - (k_+/r)J_m'(ra) - (k_e/\alpha)vJ_m(ra)\hat{K}_m \\ M_{12} &= -p_l(\beta) + (k_-/l)J_m'(la) + (k_e/\alpha)vJ_m(la)\hat{K}_m \\ M_{21} &= -p_r(\beta) - (k_+/r)J_m'(ra) - (k_e/\alpha)v^{-1}J_m(ra)\hat{K}_m \\ M_{22} &= +p_l(\beta) - (k_-/l)J_m'(la) - (k_e/\alpha)v^{-1}J_m(la)\hat{K}_m \end{aligned} \tag{9}$$

where the dash on $J_m(\cdot)$ and $K_m(\cdot)$ stands for differentiation with respect to argument, $v = \eta_e/\eta_c = (\varepsilon\mu_e/\varepsilon_e\mu)^{1/2}(1+c^2)^{1/2}$ is the ratio between free space and chiral wave impedences, and

$$\begin{aligned} p_r(\beta) &= \beta anJ_m(ra)\left[(ra)^{-2} + (\alpha a)^{-2}\right] \\ p_l(\beta) &= \beta anJ_m(la)\left[(la)^{-2} + (\alpha a)^{-2}\right] \\ \hat{K}_m &\equiv K_m'(\alpha a)/K_m(\alpha a) \end{aligned} \tag{10}$$

Finally the modal equation for the longitudinal wavenumber β is simply given by equating the determinant of $[M]_{2\times 2}$ by zero, i.e.

$$\operatorname{Det}[M]_{2\times 2} = 0 \tag{11}$$

III. Guided Mode Characteristics

Since the modes are hybrid, they should be designated as $HE_{n,s}$ or $EH_{n,s}$ where s is an integer related to the order of the roots of (11). An obvious remark on the modal (11) is that since $p_r(\beta)$ and $p_l(\beta)$ changes sign with n, one deduces that a pair of modes with azimuthal dependence $\exp(-in\varphi), n = \pm m$ will have different phase parameters; i.e. $\beta_{m,s} \neq \beta_{-m,s}$. Next we discuss mode cutoff frequencies and mode polarization states.

A. Cutoff Frequencies

As surface wave modes, cutoff occurs whenever the transverse attenuation α tends to zero. In this case $\beta \to k_e$, and each of $p_r(\beta)$, $p_l(\beta)$ and $(\hat{K}_m/\alpha)$ becomes of the order of $1/(\alpha a)^2$. Substitution in (11) and (9) gives

$$\operatorname{Lim}_{\alpha\to 0}[\operatorname{Det}(M)] = 2\text{nm}\left(k_e/\alpha^2\right)^2\left(v + v^{-1}\right)J_m(ra)J_m(la)$$

So, the modal equation reduces at cutoff to either one of the simple form:

$$J_m(ra) \equiv J_m\left((k_+^2 - k_e^2)^{1/2}a\right) = 0 \tag{12}$$

or

$$J_m(la) \equiv J_m\left((k_-^2 - k_e^2)^{1/2}a\right) = 0 \tag{13}$$

Therefore modes reduce at cutoff to two categories with cutoff frequencies governed by (12) and (13). Note that both equations do not depend on the sign of n, so that a pair of modes with $n = \pm m$ have the same cutoff frequency. A study of the modal fields under condition (12) reveals that $B = O$ (see (4), (5)) signifying that no fields are associated with the wavenumber k_-, i.e. the chiral medium behaves as one having a single wavenumber k_+. Conversely, under condition (13), $A = o$ and the fields are not associated with k_+. Of course, in the absence of chirality, (12) and (13) become identical and provide the same cutoff frequency which is determined by: $J_m((k^2 - k_e^2)^{1/2}a) = 0$.

The effect of chirality is thus to split each cutoff frequency into two, and since $k_+ > k > k_-$ one is higher and one is lower than that of the nonchiral case.

To demonstrate the effect of chirality on guided modes, the modal wavenumbers for a nonchiral rod and a chiral rod, with $\mu = \mu_e$, $\varepsilon = 2\varepsilon_e$ and $c = 0.1$, are plotted for comparison in Fig. 2 and 3 respectively. It is seen that the dominant HE_{11} mode in the nonchiral case (Fig. 2) is split into the two modes HE_{11} and $HE_{-1,1}$ in the chiral case (Fig. 3). The EH_{11} HE_{12} modes in the nonchiral case have a normalized cutoff frequency $V_c \equiv (k_c^2 - k_e^2)^{1/2}a = 3.832$. They are split into 4 modes in the chiral case, two of which have $V_c = 3.189$ and the other two have $V_c = 4.795$. Similar splitting occurs for the modes EH_{12} and HE_{13} whose cutoff occurs at $V_c = 7.016$ for the nonchiral case. This mode splitting, or bifurcation, is also displayed in Fig. 4 showing the normalized cutoff frequency V_c versus the chirality parameter c. Each cutoff frequency in the nonchiral case; $c = 0.$ is split in two branches for finite values of c.

It remains to set forth some rule for identifying modes as HE or EH. We start by identifying the zero cutoff modes as $HE_{\pm 1,1}$ in agreement with the nonchiral case. We've noticed that the ratio of coefficients B/A for any given mode is monotonically decreased towards zero as the normalized frequency V is sufficiently increased., however, the sign of B/A as it goes to zero can be positive or negative depending on the mode. So, a consistent rule for mode identification is extracted and can be stated as follows. A mode is identified as $HE_{n,s}/EH_{n,s}$ if for sufficiently high V, the ratio (nB/A) approaches zero from positive/negative values. This simple rule, used to label

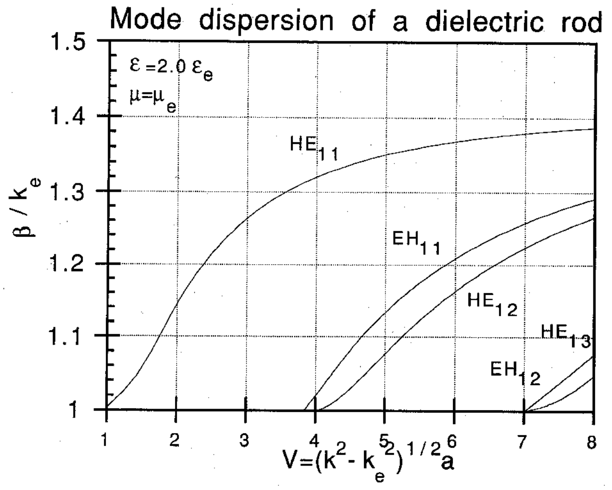

Fig. 2. Longitudinal modal wavenumber versus normalized frequency on a dielectric rod.

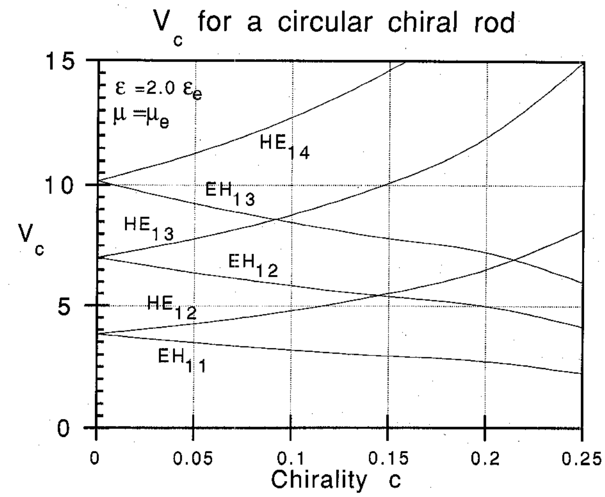

Fig. 4. Crosspolar ratio versus normalized frequency on a chiral rod.

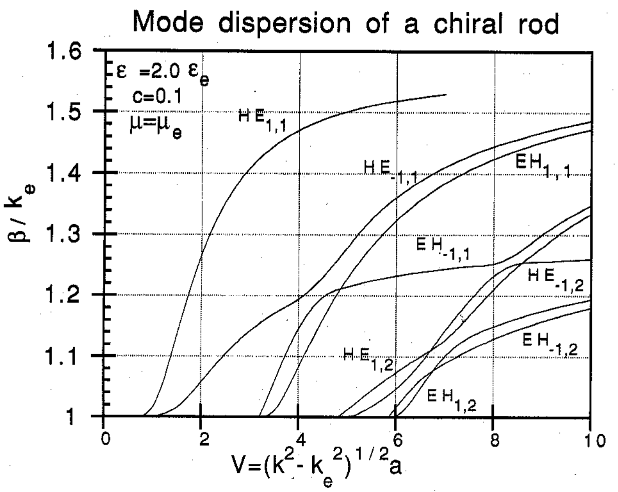

Fig. 3. Longitudinal modal wavenumber versus normalized frequency on a chiral rod.

modes in Fig. 3, is actually similar to one adopted by Bruno and Bridges [15] in connection with modes on nonchiral rods.

B. Modal Fields

To study the modal fields, it will prove fruitful to consider first the case $v = 1$. This corresponds to equal values of impedances in the chiral and external medium; i.e. $\eta_c = \eta_e$, which requires:

$$\mu/\mu_e = (\varepsilon/\varepsilon_e)(1 + c^2) \qquad 14$$

Under the condition $v = 1$, one finds from (9) that $M_{11} = M_{21}$, and $M_{12} = -M_{22}$, whence the modal equation (11) reduces to:

$$M_{11} = 0 \text{ and } B = 0 \qquad (15)$$

$$M_{12} = 0 \text{ and } A = 0 \qquad (16)$$

Thus, modes fall in two categories; in one category, corresponding to (15), the chiral material behaves as a medium with a single bulk wavenumber k_+. In the other category, corresponding to (16), it behaves as having a single bulk wavenumber k_-. Obviously, at cutoff these two categories obey (12) and (13) respectively. To study the modal fields, let us write down the transverse electric vector field of a mode in the first category. For clarity, take $n = +1$, then apart from a constant,

$$\bar{E}_t = (A/r)[J_0(r\rho)(k_+ + \beta)(\hat{x} - i\hat{y}) + J_2(r\rho)(k_+ - \beta)(\hat{x} + i\hat{y}) \exp(-i2\varphi)] \qquad (17)$$

which is valid inside the chiral rod. Here $\hat{x}$ and $\hat{y}$ are unit cartezian vectors. The first term in (17) represents an RCP field and the second term represents an LCP field. It is clear that the major polarization is RCP and as β approaches k_+, the crosspolar component approaches zero. Conversely for a mode in the second category with $n = +1$,

$$\bar{E}_t = (-B/l)[J_0(l\rho)(k_- - \beta)(\hat{x} - i\hat{y}) + J_2(l\rho)(k_- + \beta)(\hat{x} + i\hat{y}) \exp(-i2\varphi)] \qquad (18)$$

where the major polarization is LCP, particularly when β approaches k_-.

Next, in the general case $v \neq 1$, the transverse modal E field is simply a weighted sum of (17) and (18); (see (4), (5)). A suitable crosspolar factor may then be defined as the LCP field comonent at $\rho = a$ and $\varphi = 0$ divided by the RCP component at $\rho = 0$. This leads to a crosspolar factor XCP for $n = +1$ modes as

$$\text{XCP} = \frac{(\beta - k_+)J_2(ra) - (Br/Al)(\beta + k_-)J_2(la)}{(\beta + k_+) + (Br/Al)(\beta - k_-)} \qquad (19)$$

For $n = -1$ modes one can show that (19) holds for the reciprocal of XCP if the signs in front of k_+ and k_- are reversed.

The crosspolar factor is plotted in dB versus normalized frequency V for modes with $n = \pm 1$ in Fig. 5. It is seen that the XCP is monotonically decreasing with frequency for modes with $n = +1$. Modes with $n = -1$ display high positive values of XCP, signifying that they are dominantly LCP, in limited frequency bands. However, as the frequency increases sufficiently, the XCP turns to negative values and all modes eventually turn into RCP modes.

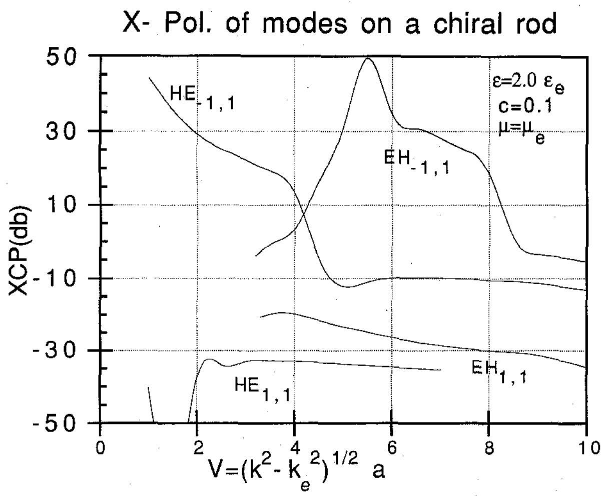

Fig. 5. Normalized cutoff frequencies of modes on a chiral rod versus normalized chirality.

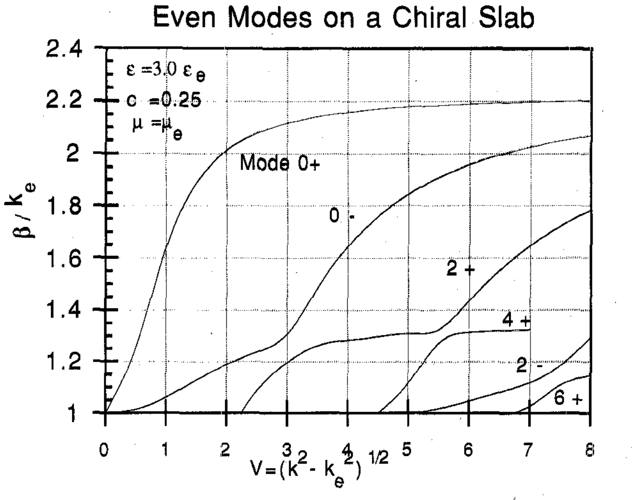

Fig. 6. Longitudinal modal wavenumber versus normalized frequency for even modes on a chiral slab.

IV. The Planar Chiral Slab

In this section, we turn attention to guided modes on a planar chiral slab as depicted in Fig. 1b. We look for modes varing as $\exp(i\omega t - i\beta z)$. Assuming uniform fields along y, one can write for the x dependence of the modal fields inside the chiral slab; $|x| \leq a$ (11–12):

$$E_y = Af(rx) + Bf(lx) \quad (20)$$

$$-i\eta_c H_y = Af(rx) - Bf(lx) \quad (21)$$

and the fields outside the slab; $|x| \geq a$:

$$E_y = \pm C_1 \exp[-\alpha(|x| - a)] \quad (22)$$

$$-i\eta_e H_y = \pm C_2 \exp[-\alpha(|x| - a)] \quad (23)$$

where $f(u) = \cos(u)$ for even modes and $f(u) = \sin(u)$ for odd modes. The $+/-$ signs are for even/odd modes. The rest of the symbols: r, l, and α have the same meaning as used in Sec II for the chiral rod.

The other field components, particularly E_z and H_z can be obtained from well known relations [e.g. 12] and the boundary conditions at $x = \pm a$ are applied to provide four equations in the unknown coefficients A, B, C_1, C_2. Eliminating C_1 and C_2 we get an equation of the form (8) with

$$M_{11} = (r/k_+)f'(ra) + (\alpha/k_e v)f(ra)$$
$$M_{12} = (l/k_-)f'(la) + (\alpha/k_e v)f(la)$$
$$M_{21} = (r/k_+)f'(ra) + (\alpha v/k_e)f(ra)$$
$$M_{22} = -(l/k_-)f'(la) - (\alpha v/k_e)f(la) \quad (24)$$

where $v = \eta_e/\eta_c$ as defined in Section II. The modal equation is again given by (11).

Mode cutoff conditions are derived by letting α tends to zero in the modal (11) and (24). This leads to two categories of mode cutoff:

$$(1)\colon f'(ra) = f'((k_+^2 - k_e^2)^{1/2}a) = 0 \text{ and } B = 0 \quad (25)$$

and

$$(2)\colon f'(la) = f'((k_-^2 - k_e^2)^{1/2}a) = 0 \text{ and } A = 0 \quad (26)$$

Noting that $f'(u) = -\sin u$ for even modes, and $f'(u) = \cos u$ for odd modes. we find that mode cutoffs are given by

$$(k_\pm^2 - k_e^2)^{1/2}a = n\pi/2 \quad (27)$$

where the $\pm$ signs refer to modes in 1st and 2nd category respectively.

The integer n above is 0, 2, 4,... for even modes and 1, 3,... for odd modes. The similarity of (25) and (26) with (12) and (13) is clear. Namely, in the absence of chirality the above two equations coincide indicating that one cutoff frequency in the nonchiral case splits into two when chirality is introduced.

A numerical example showing mode dispersion of even modes versus normalized frequency on a chiral slab is given in Fig. 6. Here $\mu = \mu_e, \varepsilon = 3\varepsilon_e$ and $c = 0.25$. Mode order is designated by an even integer n which relates to mode cutoff as given by (27), and a plus /minus sign depending on whether the mode belongs to category 1 or 2 respectively. For example, the mode labelled by "2+" has cutoff given by $(k_+^2 - k_e^2)^{1/2}a = \pi$ while the mode "2−" has cutoff given by $(k_-^2 - k_e^2)^{1/2}a = \pi$. Obviously modes labelled by 0+ and 0− have zero cutoff frequency but different β's at finite frequencies. It is worth noting that the above mentioned mode designation is merely a convention and any other convention may as well be used. For example,we could use the designation HE_n for modes with cutoff given by (25) and EH_n for modes with cutoff given by (26).

To study the modal fields, we first consider the important special case $v = 1$, or equivalently when (14) holds. In this case $M_{11} = M_{21}$ and $M_{12} = -M_{22}$, whence the modal equation splits into two mode categories for which $M_{11} = 0$ and $B = 0$ in category 1 and $M_{12} = 0$ and $A = 0$ in category 2. It is clear that in this special case the chiral medium behaves as one having a single bulk wavenumber k_+ or k_- (see (24)). The corresponding transverse vector E field is expressed for category 1 modes by:

$$\bar{E}_t = (iAf(rx)/2k_+)[(k_+ + \beta)(\hat{x} - i\hat{y}) - (k_+ - \beta)(\hat{x} + i\hat{y})] \quad (28)$$

and for category 2 modes by

$$\bar{E}_t = (iBf(lx)/2k_-)[(k_- + \beta)(\hat{x} + i\hat{y}) + (k_- - \beta)(\hat{x} - i\hat{y})] \quad (29)$$

It is clear that the major polarization of modes in category 1 is RCP and for category 2 is LCP.

V. Concluding Remarks

A rigorous analysis for guided surface wave modes on a chiral rod and a planar chiral slab embedded in an homogeneous isotropic medium has been presented. Simple closed forms for the cutoff frequencies of the modes have been derived. It is found that for each cutoff frequency in the absence of chirality, there exist two cutoff frequencies in the chiral case; the lower of the two is determined by the wavenumber k_+ alone and the higher is determined by k_- alone (12), (13) and (25), (26).

Guided Modes on the chiral rod or slab are always hybrid and are generally a superposition of RCP and LCP field components. However, as the frequency is sufficiently increased, each mode tends to have β approaching k_+, hence each mode tends to become RCP. (assuming a right-handed chiral medium).

The special case of equal chiral and external medium impedances is of particular importance. In this case the modes fall into two categories in which the chiral medium behaves as having a single bulk wavenumber k_+ or k_-. Modes in the first category are dominantly RCP and in the second are dominantly LCP. A chiral rod under this condition can be adapted for use as an antenna or reflector antenna feed radiating low crosspolar fields over a very wide frequency band. If $\mu_e = \mu$, condition (14) for equal impedences reduces to $\varepsilon_e = \varepsilon(1+c^2)^{1/2}$. A clad of sufficient thickness having this value of ε_e will secure the low crosspolar behavior. Even, if the outside medium is merely air, results presented in Fig. 5 show that low XCP values can be maintained by the low order modes over a wide frequency range. By proper excitation, one should be able to efficiently excite the lower order modes and reduce higher order modes.

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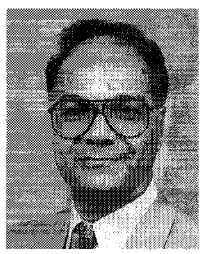

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