DIRECTIONAL COUPLER ANALYSIS AS AN OPTICAL POWER TRANSFER FOR TM$_{oo}$ MODE

A. Rubiyanto, D. N. Widayanti, A. Y. Rohedi, Suryadi

Abstract.
The analysis of the optical power transfer in the linear step index directional-coupler based on the coupled-mode theory is inaccurate for a small gap. This problem has been previously overcome by using the normal-modes approximation. Generally, this approximation has been solved by numerical methods such as Fourier transform or finite difference. In this paper, the Helmholtz equation is, instead, analytically solved by using a characteristic matrix of multilayer waveguides in order to find the electric field and its propagation constant of the normal-modes. Ti:LiNbO$_3$ system, is used in the simulation which has a film of index ($n_f$) = 2.234, substrate material of index ($n_s$) = 2.214, cover material of index ($n_k$) = 1, and laser wavelength ($\lambda$) = 1.33 m. The result of simulation indicates that the relations between width gap ($s$), depth guide ($d$), width guide ($h$), and also coupling length ($L_c$) are non-linear.

1. INTRODUCTION

The directional-couplers are the major interest in integrated optics, since it have potential applications in optical communications to be used as low-loss optical switches [1], high speed modulators [2], polarization splitter [3], integrated acousto-optical heterodyne interferometer[4] and wavelength demultiplexer/multi-plexer [4]. Due to coupling effect, optical power can be transferred from one waveguide to
another adjacent waveguide as a result of the overlap in the evanescent fields of the two guides. The amount of power transferred between the waveguides depends upon the waveguide parameters, i.e., the guided wavelength, the confinement of the individual waveguides, the separation between them, the length over which they interact, and the phase mismatch between the individual waveguides [5]. The power transfer of two waveguides in the directional-couplers has been treated extensively utilizing the coupled-mode method, but as shown in [6] this method becomes less accurate when the waveguides get too close. An alternative choice is the normal-modes approximation. This approximation taken full account of the entire structure and solves for modal indices and guided fields of the supermodes. In the normal-modes approach, the characteristic of the directional-couplers are then represented by interferences between the guided fields of the supermodes [7], i.e symmetrical and asymmetrical modes. In practical, the directional-couplers are made in 3-D structure, consist of waveguides with finite lateral dimensions. In order to obtain the exact solutions of normal modes, the 3-D is usually reduced to 2-D guides structure [7],[8]. Hence in the 2-D guides, the two parallel waveguides with their surrounding medium can be considered as a single structure, so that the normal-modes of the such structure can be solved by method of multilayer waveguides. In this paper we use the multilayer waveguides to formulate the optical electric fields in the symmetrical directional-couplers. The expression of such the guided fields derived by method of multilayer waveguides given by Kogelnik [9], and Rohedi [10].

2. MULTILAYER WAVEGUIDES

The fundamental component of the integrated optics is optical waveguide. The simplest optical waveguide is the planar slab guide shown in Fig 1, where a planar film of refractive index \( n_f \) is sandwiched between a substrate and a cover material with lower refractive indices \( n_s \) and \( n_c \) (\( n_f \geq n_s \geq n_c \)). The structure of a multilayer waveguide structure and its coordinate system are shown in Fig.1. The direction of propagation is in the z direction, while the variation of the media is in the x direction. For simplicity the structure is assumed to be one dimensional and lossless. Basically the multilayer waveguide can be considered as three-layer guides, of which a stack consists of N layers with parallel boundaries is sandwiched between a substrate and a cover material. According to

\[
\frac{\partial^2 H_{yi}}{\partial x^2} - \gamma_i^2 H_{yi} = 0, \quad i = s, f, c
\]

where \( \gamma_c \) (propagation constant at cover), \( \kappa_f \) (film layer), and \( \gamma_s \)(substrate layer) define as:

\[
-\gamma_c^2 = n_c^2 k_0^2 - \beta^2 , \quad \kappa_f^2 = n_f^2 k_0^2 - \beta^2 , \quad -\gamma_s^2 = n_s^2 k_0^2 - \beta^2
\]

hereinafter conducted by applying of boundary condition to \( H_y \) representing mathematical solution from equation(1-2) and continuity \( E_z \), successively at \( x=d/2 \) and \( x=-d/2 \), where at second of the x are \( H_{yc} = H_k \) and \( H_{ys} = H_s \). So that transversal component of the magnetic field which propagate in third layer can be wrote as:

\[
H_{yc} = H_c e^{-\gamma_c(x-d/2)}, \quad x > d/2
\]
Directional Coupler Analysis

Figure 1: The geometry of single optical waveguide

\[ H_{yf} = H_f \cos(\kappa_f(x - d/2) + \phi_k), d/2 < x < d/2 \]  \hspace{1cm} (4)

\[ H_{yf} = (-1)^m H_f \cos(\kappa_f(x + d/2) + \phi_k), d/2 < x < d/2 \]  \hspace{1cm} (5)

\[ H_{ys} = H_s e^{-\gamma_s(x-d/2)}, x < d/2 \]  \hspace{1cm} (6)

where \( H_c, H_f \) and \( H_s \) are the amplitude of transverse component of magnetic field at third layer. While \( \phi_c \) and \( \phi_s \) are respectively given by:

\[ \tan \phi_c = \left( \frac{n_f^2}{n_c^2} \right) \left( \frac{\gamma_c}{\kappa_f} \right) \]  \hspace{1cm} (7)

\[ \tan \phi_s = \left( \frac{n_f^2}{n_c^2} \right) \left( \frac{\gamma_s}{\kappa_f} \right) \]  \hspace{1cm} (8)

The normalization of magnetic field guided in equation (6-8):

\[ H_y = \begin{cases} 
H_f \cos(\phi_k) e^{-\gamma_s(x-d/2)} : & \text{if } x > d/2 \\
(-1)^m H_f \cos(\kappa_f(x + d/2) - \phi_s) : & \text{if } x < d/2 \\
H_f \cos(\phi_k) e^{-\gamma_s(x-d/2)} : & \text{if } d/2 < x < d/2 
\end{cases} \]  \hspace{1cm} (9)

By applying of boundary condition at parallel field with the boundary area that is \( H_y \) and \( \frac{\partial H_y}{\partial x} \) to equation(6-9), hence the dispersion relationship for the TM mode is given in the form:

\[ 2\kappa_f d - 2\phi_s - 2\phi_k = 2m\pi \]  \hspace{1cm} (10)

where \( m = 0, 1, 2, 3 \), are order of modes. Form the normalization from relation dispersion for the TM mode:

\[ V \left( \sqrt{\frac{n_f}{n_s}} \sqrt{1-b} \right) = m\pi + \tan^{-1} \sqrt{\frac{b}{1-b}} + \tan^{-1} \sqrt{\frac{b + a(1-bc)}{1-b}} \]  \hspace{1cm} (11)
With the normalized frequency, $V$:

$$V = k_o d \sqrt{n_f^2 - n_s^2} \quad (12)$$

The normalized effective refractive index, $b$:

$$b = \left[ \frac{N^2 - n_s^2}{n_f^2 - n_s^2} \right] \left[ \frac{n_f^2}{n_s^2 q_s} \right] \quad (13)$$

where $N$ is effective refractive index. The reduce factor, $q_s$ given by:

$$q_s = \frac{N^2}{n_f^2} + \frac{N^2}{n_s^2} - 1 = \frac{n_f^2/n_s^2}{(1 - b) + bn_s^2/n_f^2} \quad (14)$$

While asymmetry factor of refractive index at cover and substrate layer, $a$ is given by:

$$a = \frac{n_s^4 - n_k^2}{n_k^2 n_f^2 - n_s^2} \quad (15)$$

The factor $C$ is defined as:

$$c = \left[ 1 - \frac{n_s^2}{n_f^2} \right] \left[ 1 - \frac{n_k^2}{n_f^2} \right] \quad (16)$$

### 3 DIRECTIONAL COUPLER

The geometrical structure of directional coupler is shown in Fig. 2 with $s$ is gap distance between the waveguides, $h$ is width of each canal along as the lateral direction, $d$ is depth of each canal, and $Z$ is interaction length of the two waveguide. The depth and width of each canal have been designed such that each guide only support single guide mode. The transfer of optical energy can be explained by using the coupled mode theory. Based on this theory if the gap distance is big enough, hence elementary evanescent field from second of canal (symbolised by $A$ and $B$) alongside gap area do not generate the coupling, so that at each a optical wave at the basic mode can propagate individually. On the contrary if the distance of between canal very small hence evanescent field alongside is giving each other and coupling on the way of propagation:

$$\frac{\partial A(z)}{\partial z} = -j \kappa_{AB} B(z) e^{-(\beta_B - \beta_A)z} \quad (17)$$

$$\frac{\partial B(z)}{\partial z} = -j \kappa_{BA} A(z) e^{(\beta_B - \beta_A)z} \quad (18)$$
Directional Coupler Analysis

where $\kappa_{AB} = \kappa_{AB} = \kappa$ coupling coefficient. $A(z)$ and $B(z)$ are defined as:

$$A(z) = A e^{-j\gamma z} e^{-j\Delta z}$$  \hspace{1cm} (19)

$$B(z) = B e^{-j\gamma z} e^{-j\Delta z}$$  \hspace{1cm} (20)

where $\Delta = \frac{\beta_s - \beta_a}{2}$ is the phase mismatch. Equation (21) substitution by equation (23-24) and wrote:

$$A = \frac{\kappa B}{\gamma + \Delta}$$  \hspace{1cm} (21)

Equation (21) substitution by equation (22-23) and resulted:

$$B = \frac{\kappa A}{\gamma - \Delta}$$  \hspace{1cm} (22)

Solution from equation (21-22) are:

$$A(z) = \left( A_s e^{-j\sqrt{\kappa^2 + \Delta^2} z} + A_a e^{-j\sqrt{\kappa^2 + \Delta^2} z} \right) e^{-j\Delta z}$$  \hspace{1cm} (23)

$$B(z) = \left( B_s e^{-j\sqrt{\kappa^2 + \Delta^2} z} + B_a e^{-j\sqrt{\kappa^2 + \Delta^2} z} \right) e^{-j\Delta z}$$  \hspace{1cm} (24)

with, $B_s = \frac{\kappa A_s}{\sqrt{\kappa^2 + \Delta^2}}$, $B_a = \frac{\kappa A_a}{\sqrt{\kappa^2 + \Delta^2}}$

Optical energy transfer between the canal in the directional coupler became by the coupling distance ($L_c$), which is defined as:

$$L_c = \frac{\phi}{\Delta \beta} \text{ or } L_c = \frac{\phi}{2\kappa}$$  \hspace{1cm} (25)

where $\Delta \beta = \beta_s - \beta_a$
4. CHARACTERISTICS MATRIX METHOD
Charactristic Matrix Method is method which aim to determine $\beta$ and $H_y$ of Helmholtz equation, equation (1). The formulation of the matrix characteristic at each layer for the TM Mode are symbolising tangensial field as:

$$U(x) = H_y$$

$$V(x) = -\frac{j}{n^2} \frac{\partial U}{\partial x} = -\frac{j}{n^2} \frac{\partial H_y}{\partial x} = -\frac{j}{n^2} \omega \varepsilon_o E_z$$

Equation of the propagation of optical wave for TM Mode in the film layer:

$$\frac{\partial^2 U}{\partial x^2} + \kappa^2 U = 0$$

Equation (32) above having solution:

$$U = A e^{-j\kappa x} + B e^{j\kappa x}$$

$$V = -\frac{j}{n^2} \frac{\partial U}{\partial x} = \frac{\kappa}{n^2} \left[ -A e^{(-j\kappa x)} + B e^{j\kappa x} \right]$$

Hence $U$ and $V$ can be expressed in the form of matrix multiplication and vector column:

$$\begin{bmatrix} U \\ V \end{bmatrix} = \begin{bmatrix} e^{-j\kappa x} & e^{-j\kappa x} \\ -\frac{\kappa}{n^2} e^{-j\kappa x} & e^{j\kappa x} \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix}$$

If at the first layer that is at the area $x_o \leq x_1$, specified by $U(x = x_o) = U_o$ and $V(x = x_o) = V_o$, hence equation (34) becoming:

$$\begin{bmatrix} U_o \\ V_o \end{bmatrix} = \begin{bmatrix} e^{-j\kappa x_o} & e^{-j\kappa x_o} \\ -\frac{\kappa}{n^2} e^{-j\kappa x_o} & e^{j\kappa x_o} \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix}$$

So that $\begin{bmatrix} A \\ B \end{bmatrix}$ can be expressed as:

$$\begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} \frac{1}{2} e^{j\kappa x_o} - \frac{n^2}{2\epsilon} e^{j\kappa x_o} \\ -\frac{1}{2} e^{-j\kappa x} - \frac{n^2}{2\epsilon} e^{j\kappa x_o} \end{bmatrix} \begin{bmatrix} U_o \\ V_o \end{bmatrix}$$

From equation (36) got:

$$A = \frac{1}{2} \left( U_o - \frac{n^2}{\kappa} V_o \right) e^{j\kappa x_o}$$

$$B = \frac{1}{2} \left( U_o + \frac{n^2}{\kappa} V_o \right) e^{-j\kappa x_o}$$

Equation (37-38) are substituted into equation(32-33):

$$U = U_o cos(\kappa(x - x_o)) + \frac{n^2}{\kappa} V_o sin(\kappa(x - x_o))$$
\[ V = \frac{j \pi^2}{\kappa} U_o \sin(\kappa(x - x_o)) + V_o \cos(\kappa(x - x_o)) \] \hspace{1cm} (37)

If expressed in the form of the matrix multiplication and vector column become:
\[
\begin{bmatrix}
U \\
V
\end{bmatrix} =
\begin{bmatrix}
\cos(\kappa(x - x_o)) & j \frac{\pi^2}{\kappa} \sin(\kappa(x - x_o)) \\
j \frac{\pi^2}{\kappa} \sin(\kappa(x - x_o)) & \cos(\kappa(x - x_o))
\end{bmatrix}
\begin{bmatrix}
U_o \\
V_o
\end{bmatrix}
\] \hspace{1cm} (38)

At the \( n \)th layer, \( x = x_n, \kappa = \kappa_n \hspace{0.5cm} U(x = x_m) = U_n \) and \( V(x = x_n) = V_n \) got:
\[
\begin{bmatrix}
U_n \\
V_n
\end{bmatrix} =
\begin{bmatrix}
\cos(\kappa_n(x_n - x_{n-1})) & j \frac{\pi^2}{\kappa_n} \sin(\kappa_n(x_n - x_{n-1})) \\
j \frac{\pi^2}{\kappa_n} \sin(\kappa_n(x_n - x_{n-1})) & \cos(\kappa_n(x_n - x_{n-1}))
\end{bmatrix}
\begin{bmatrix}
U_{n-1} \\
V_{n-1}
\end{bmatrix}
\] \hspace{1cm} (39)

If the width of each layer \( h_i = x_i - x_{i-1} \), that way also propagation constan of layer: \( \kappa_i = \sqrt{\kappa^2 n_i^2 - \beta^2} \) by \( i = 1, 2, 3, \ldots, n \). So that the matrix form in general:
\[
\begin{bmatrix}
U_i \\
V_i
\end{bmatrix} = M_i
\begin{bmatrix}
U_{i-1} \\
V_{i-1}
\end{bmatrix}
\] \hspace{1cm} (40)

\( M_i \) express the characteristic matrix to each layer \( i \)-th from film layer optical guide, that is:
\[
M_i =
\begin{bmatrix}
\cos(\kappa_i h_i) & j \frac{\pi^2}{\kappa_i} \sin(\kappa_i h_i) \\
j \frac{\pi^2}{\kappa_i} \sin(\kappa_i h_i) & \cos(\kappa_i h_i)
\end{bmatrix}
\] \hspace{1cm} (41)

Thereby vector of the tangensial field tangensial at the area of boundary substrat-film and film-cover that is \( \begin{bmatrix} U_o \\ V_o \end{bmatrix} \hspace{0.5cm} \begin{bmatrix} U_n \\ V_n \end{bmatrix} \) can be connected due to
\[
\begin{bmatrix}
U_n \\
V_n
\end{bmatrix} = M_n M_{n-12} M_1
\begin{bmatrix}
U_o \\
V_o
\end{bmatrix} =
\begin{bmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{bmatrix}
\begin{bmatrix}
U_o \\
V_o
\end{bmatrix}
\] \hspace{1cm} (42)

By matrik \( M = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \) is referred as the multi layer matrix characteristic.

The result of above formulation indicate that if each layer by the multi layer matrix characteristic, hence all area of the film also deputized by the multi layer matrix characteristic which are representing multiplication from all matrix characteristic in each layer alongside film area. To get the equation of the dispersion relationship of the planar wave guide for the TM Mode, in the firs it is originally evaluated by the electrics field and magnetic field which are tangensial alongside the substrat area, that is at \( x = x_o \), what is the in form of:
\[
U_s = B_s e^{\gamma_s (x - x_o)}
\] \hspace{1cm} (43)

\[
V_s = -\frac{j}{n_s} \gamma_s B_s e^{\gamma_s (x - x_o)}
\] \hspace{1cm} (44)

and alongside the cover area, that is at \( x_n \)
\[
U_k = A_k e^{\gamma_k (x - x_n)}
\] \hspace{1cm} (45)
By applying the continuity condition of tangential field at the boundary area substrate-film, at \( x=x_o \), and also at \( x=x_n \) found:

\[
U_o = U_s = B_s \\
V_o = V_s = -j \frac{\gamma_s}{n_s^2} B_s
\] (47)

\[
U_n = U_k = B_k \\
V_n = V_k = -j \frac{\gamma_k}{n_k^2} B_k
\] (48)

If the value \( U_o, V_o, U_n \) and \( V_n \) included into equation (45) found by the relation:

\[
A_k = m_{11} B_s - j \frac{\gamma_s}{n_s^2} B_s \\
j \frac{\gamma_s}{n_k^2} A_k = m_{21} B_s - j \frac{\gamma_k}{n_k^2} m_{22} B_s
\] (49)

By elimination of \( A_k \) and \( B_s \) from equation (52), hence found by the equation of dispersion relationship for the optical wave of TM mode:

\[
j \left( m_{11} \frac{\gamma_k}{n_k^2} + m_{22} \frac{\gamma_s}{n_s^2} \right) + m_{12} \frac{\gamma_s \gamma_k}{n_s^2 n_k^2} - m_{21} = 0
\] (50)

5. RESULT AND DISCUSSION

5.1 The Accuration test of Matrix characteristics Method at the Normalization of Effective Refractive Index \( b \) as Function of Normalization Frequency \( V \)

To test the accuracy of method of matrik characteristic, hence it have previously conducted by comparison of the result with the analytical method, by taking simple example that is effective refractive index relation normalization, \( b \) and normalization frequency, \( V \) and also the pattern of magnetic field at guide of wave slab. An analytically by using equation(13) knowable to hence assess the \( b \) of guide of wave slab, beforehand determine the value \( n_{fs}, V, m \) and \( a \). By \( \gamma_k \) (propagation constan of optic wave as long as cover layer), \( \kappa_f \) (layer film) and \( \gamma_s \) (substrate layer) defined [10]: \( \gamma_k = \frac{V}{\sigma} \sqrt{\frac{1}{n_{fs} n_{ks}} - \frac{1}{n_k^2}} \sqrt{b + a(1 - bc)} \), \( \kappa_f = \frac{V}{\sigma} \sqrt{\frac{1}{n_{fs}} - \frac{1}{n_{fs}^2}} \), \( \gamma_s = \frac{V}{\sigma} \sqrt{\frac{1}{n_s^2}} \)

where \( n_{fs} \) represent the comparison of refractive index film-substrate, what its value have to be bigger than 1, where at this calculation is taken by \( n_{fs} = 1.01 \). From equation (18) found by value \( n_{fk} \), that is comparison of film-cover refractive
Figure 3: Relationship of disperssi normalization of a guide of wave of moda TM to three order

index equal to: \( n_{fk} = \sqrt{\frac{2a \left( 1 - \frac{1}{n_{fs}} \right)}{-1 + \sqrt{1 + 4a \left( \frac{1}{n_{fs}} \right) - 4a \left( \frac{1}{n_{fs}} \right)^2}}} \)

While \( n_{ks} \) is comparison of refractive index kover-substrate which defined as:
\( n_{ks} = \frac{n_{ks}}{n_{fk}} \)
Later the magnitude of \( b \) is obtained from compared between the analytical method and the method of matrix characteristic, equation (53), as shown in Table 1.

Table 1. The calculation of effective refractive index with the analytical method and matrik of characteristic

<table>
<thead>
<tr>
<th>m</th>
<th>V</th>
<th>a</th>
<th>( b_{analytic} )</th>
<th>( b_{matrix} )</th>
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<tr>
<td>0</td>
<td>2</td>
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<tr>
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</tr>
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<td>0.9</td>
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</tr>
</tbody>
</table>
The equation of dispersion relationship for the optical wave TM mode can be expressed alongside guide the wave planar in the form of the curve of between V and b, either through analytical and also matrix characteristic, what its result is shown at Fig. 3.

5.2 Pattern of magnetic field at directional coupler

The theory has been test for a structure consisting of two parallel slab guides $d = 2 \mu m$ wide each, separated by a distance of $h = 3 \mu m$. Typical values for refractive indexes of $LiNbO_3$ and $Ti : LiNbO_3$ have been chosen for substrate and guides, respectively. A numerical computation has been carried wide for each guide with an index 2,201, surrounded by a medium with an index of 2,2, the illumination resulting is shown in Fig. 4.

The pattern of magnetic field at $z=0$ and also seen the propagation of the wave which is couple into canal 1 that shown in above Figure. Then the optical wave transfer to the other canal as long as direction of $z$. The power carried by these structures is found to periodically exchange between them with distance. According to normal-mode approximation, coupling length i.e the distance required for the exchange power has been transferred to the opposite waveguide is defined as $L_c$. In Figure 5 it is shown that progressively increase width gap (s) hence coupling length ($L_c$) also progressively growing larger.

It can be explained if the width gap (s) increase, so that the effective of constant propagation of asimetri mode, $\beta_0$ progressively come near the effective value of propagation symmetry mode. At wide of big gap that is $s \geq 4 \mu m$ an effective value propagation constant is equal, so that $\Delta \beta = 0$, as a result assess the $L_c$ very big. Explainable the mentioned by using theory of the mutually couple mode. Based on
Figure 5: Relation width gap $s$ with coupling length ($L_c$) for variable of $h$

this theory when the wide of each gap of canal very small, hence elementary wave evanescent moda alongside the gap area is giving each other perturbation, coupling between both causing the amplitude of optical wave which propagate at each canal change as long as distance its propagation. On the contrary if the width of gap is big enough, hence elementary wave evanescent moda from both canal alongside gap area do not generate the coupling, because of there no binding evanescent from optic wave which transmission into canal 1 tired of canal 2, so that at each canal of optic wave at the elementary moda can propagate individually.

Variation of the deepness, $d$ is also influence the coupling length ($L_c$), where progressively increase the $d$ hence $L_c$ also progressively growing larger. Explainable the mentioned as follows, that progressively increase $d$ depthness hence bind the laser ray which transmission also progressively increase a lot of so that the energi laser ever greater also. With the existence of energi laser which progressively growing larger, hence energy of optic wave at canal one can make a move to canal two, longly is ever greater coupling (see Figure 6).

Wide Variation of the lateral ($h$), $h$ also influence the coupling length ($L_c$), where progressively increase the $h$ hence $L_c$ also progressively growing larger. Explainable $h$ mentioned as that happened $d$ deepness accretion, $d$, that progressively increase wide $h$ lateral, $h$ hence bind the laser ray which transmission also progressively increase so that energi laser also progressively growing larger. With the existence of energi laser which progressively growing larger, hence energy of optic wave of $h$ canal. one can make a move to canal two, longly $h$ is ever greater coupling.
Figure 6: Relation width gap \( s \) with coupling length \( L_c \) for variable of \( d \)

Figure 7: Relation width gap \( s \) with coupling length \( L_c \) for variable of \( h \)
6. CONCLUSION.
The result of simulation indicate that the increasing of width gap (s), depth guide (d), width guide (h), hence apart at the time of the happening of energy transfer between the canal as long of coupling, $L_c$ also progressively growing larger.

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A. Rubiyanto, D. N. Widayanti, A. Y. Rohedi, Suryadi: Department of Physics, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia.
E-mail: arubi@physics.its.ac.id