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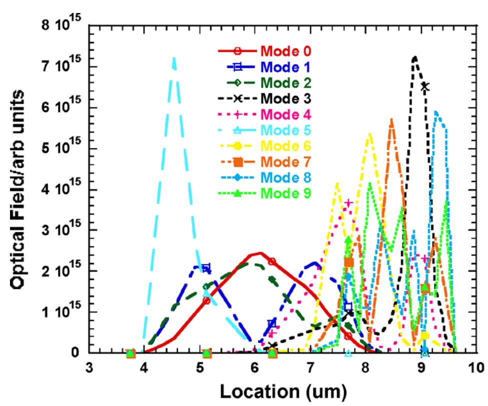

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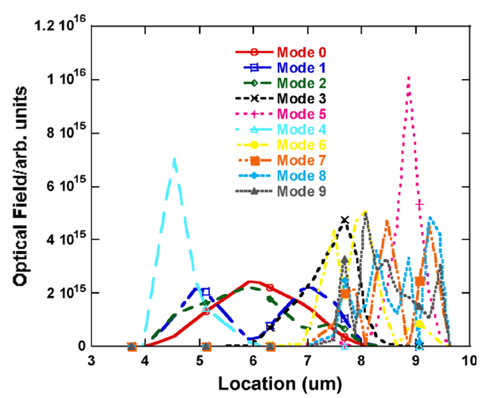

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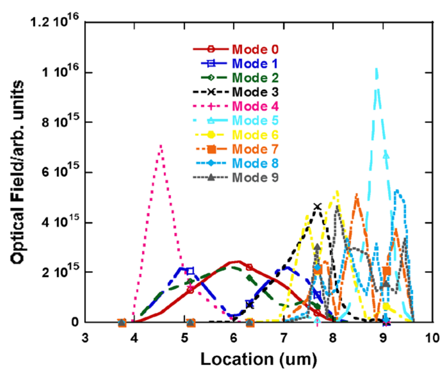

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Wavelength Dependence of Transverse Mode Coupling With/Without E-Block of GaN Laser Cavity

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Abstract: Transverse mode wavelength dependence in the gallium nitride (GaN) laser cavity is a new topic. Modal analysis simulations are run to optimize the blue GaN-based laser diode with a wavelength of 400, 430, and 460 nm. It is shown that the optical confinement factor (OCF) has a strong dependence on wavelength of emission and electron-block (e-block) thickness. The OCF can be changed from 4.9% at a 460-nm wavelength to 7.6% at 400 nm, which is a 55% difference. The effect of adding an e-block layer of different widths is also investigated with results showing that an e-block layer can change optical confinement by 14% at 460 nm wavelength and 13% at 400 nm wavelength. The bottom n-GaN layer thickness is optimized between 0.1 and 7 μm. It is found that a thin buffer layer improves optical mode distribution by reducing the ghost mode.

Index Terms: Gallium-nitride laser diode, optical mode, optical mode confinement.

1. Introduction

The visible color spectrum has three primary colors, i.e., red, green and blue, from which all colors can be generated. Red and green have been implemented, respectively, but blue has been the most challenging to create with a laser diode. At the present time, the gallium nitride (GaN) material has proven to be the best option for short wavelength laser emission. Although GaN lasers have been implemented, currently, they have a high threshold current and a short lifetime. A major cause for these problems is the anti-guided-like behavior of the waveguide mode associated with the n-GaN buffer layer and multilayer waveguides. This is also referred to as the "ghost mode" phenomenon [1], [2]. As a result of ghost modes, GaN lasers usually lase at a higher order mode. The optical confinement of this mode is also very low (around 5%), which contributes to the high threshold current. High threshold currents lead to lower life expectancy [3], [4]. Currently, optical waveguide mode optimization is still a very active research topic in GaN laser diode design, as in [5] in Green GaN Laser diode. In this paper, we investigate which modes the same waveguide structure can support if the wavelength of the blue GaN LD is varied. In other words, we study the transverse modes variation in the laser cavity according to the operational wavelength.

Recently, a thin electron-block (e-block) layer with a quite-low refractive index value placed above the Multi-Quantum Well (MQW) is involved in GaN LD design. An electron-blocking layer is put between the p-doped side and the active layer to prevent leakage of electrons to the p-doped side.

TABLE 1

Laser diode structure with variable e-block and fixed substrate width for 400-nm simulation

Layer	Thickness (nm)	Refractive index
p-GaN (contact)	50	2.55
p-AlGaN (cladding)	500	2.53
p-GaN (waveguide)	100	5.55
p-AlGaN (e-block)	0, 20, or 35	2.42
n-GaN	15	2.55
InGaN (5QWs)	67	2.685
n-GaN (waveguide)	100	2.55
n-AlGaN (cladding)	800	2.53
n-GaN (buffer)	4000	2.55
Sapphire(Substrate)	4000	1.77

It is used to confine electron/hole carrier recombination to the active region where light is most likely to result. Any recombination outside the active layer will likely not radiate or radiate at a frequency for which the laser is not designed. The laser diode's lifetime is also dependent on the number of nonradiative recombination centers [6].Therefore, leakage is a problem for III-Nitride compound semiconductors because they require a relatively high injection current due to their low hole concentration [7]. Although the e-block lowers electron carrier leakage, it also increases the threshold current by adding unwanted resistance and blocks p-side holes from entering the active region [8]. It is a very important layer which improves the laser's efficiency. Usually, higher carrier leakage occurs when a higher injection current is used. The e-block plays an even more important role when a high injection current is necessary as with III-Nitride lasers. Although the main purpose of the e-block is to decrease carrier leakage, its influence on the optical characteristics of the laser cavity is not fully studied or understood. Therefore, we would like to address its effect on the optical characteristics of the laser. In this paper, we present some new results on how the e-block influences optical modes in the GaN laser diode cavity.

First, we present the 1-D optical mode analysis of the GaN laser emitting a wavelength of 460 nm. These results are compared to the results of simulations run with a wavelength of 400 nm and 430 nm to see if the optical confinement factor (OCF) has any dependence on the wavelength. Second, the bottom n-GaN layer thickness design is studied and optimized from 0.1 to 7 μm. Finally, we also explore the effect of using an e-block layer in our laser diode design throughout the paper.

2. Simulation Model

We study the waveguide structure of InGaN/GaN-based MQW laser with separated confinement heterostructure (SCH) at emission wavelengths of 400, 430, and 460 nm, which is shown in Table 1. Our primary goal for this work is to analyze the transverse mode pattern and optical field confinement factor variation. We use a 1-D laser model for simplicity. Moreover, the model also reveals important optical characteristics of the MQW GaN laser diode. We model the laser diode resonator properties of each layer with standard material properties. The light propagation through the laser is found by solving Maxwell's equations. We assume that our structure has strong refractive index guiding; therefore we approximate Maxwell's equations with the Helmholtz equation. The strength and location of each mode of propagation are calculated by simultaneous iteration of the Helmholtz equation which then allows the OCF to be calculated.

Helmholtz equation:

$$\left[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+k_0^2\left(\varepsilon(x,y)-n_{eff,m}^2\right)\right]E_m(x,y,z)=0 \tag{1}$$

where $E_m(x,y,z)=E_m\exp(ik_0 n_{eff,m}z)$, k_0 is the free-space vector, and $\varepsilon(x,y)$ is the complex dielectric constant profile of the multilayer structure. The dielectric constant is a material parameter,

TABLE 2

Optical confinement factors of each mode $\lambda = 460$ nm

Mode	Optical Confinement Factor (%)		
	no e-block.	**e-block of 35nm width**	**e-block of 20nm width.**
(0,0)	0.0002463	0.000058	0.000001
(1,0)	0.0015903	0.000297	0.000467
(2,0)	0.0023530	0.000313	0.000525
(3,0)	4.9179800	0.021712	0.056455
(4,0)	1.7050500	0.000028	0.000137
(5,0)	0.0001122	5.016970	5.614760
(6,0)	0.1647760	0.454514	0.294066
(7,0)	0.1138420	0.101090	0.107288
(8,0)	0.7883330	1.112340	0.971194
(9,0)	1.332770	1.527570	1.447420

which is adjusted according to the wavelength for all layers. The refractive index of materials varies with the wavelength (and frequency) of light. This is called dispersion. For a more accurate description of the wavelength dependence of the refractive index, the Sellmeier equation is used. It is an empirical formula that works well in describing dispersion [9], [10]. The eigenvalues are given by the effective refractive index $n_{eff,m}$. The frequency $k_0 = \omega_0/c$ of the mode is solved and is set to correspond to the quantum well band gap energy.

At the beginning of GaN LD development, a diode with a 405-nm wavelength (ultraviolet) was developed. Most laser cavity designs are focused around this wavelength [11]. In recent years, GaN LDs around 450 nm have been studied intensively, and a similar laser cavity design is used for both 400-nm and 450-nm cases. Our basic simulation laser diode structure is based on the same structure used in [11]. In this paper, we simulate multiple wavelengths (400, 430, and 460 nm) instead of only simulating 400 nm. We reveal the optical mode variation with wavelength to identify if our current laser structure is appropriate for the blue GaN LD design. Table 1 lists the layers of the structure with its thicknesses and refractive indices at a 400-nm wavelength. The basic design of the laser diode is a PN junction with an active layer between the p and n cladding layers. The active layer consists of five quantum wells where the optical gain allows the stimulated emission of light. An electron-blocking layer is put in between the p-doped side and the active layer to prevent leakage of electrons to the p-doped side. The e-block is a p-doped layer itself which has a higher band gap than the adjacent layers. Any leakage current drops the efficiency of the laser because of dissipation of nonlasing energy.

3. Simulation Results

3.1. Wavelength Dependence of Optical Mode With and Without e-block

The active layer determines the lasing wavelength. Usually the mode in the waveguide structure with the highest OCF is the lasing mode. Other modes are also present in the laser cavity and try to compete with the lasing mode and reduce the laser efficiency. For example, the buffer layer has a significantly larger thickness and has waveguide like properties due to the smaller refractive index of the layers beside it, which support the ghost (nonlasing) mode in the laser structure [12]. It is preferred to reduce the OCF of the nonlasing modes and improve the efficiency of the laser. Here, we present new data on how the e-block affects the laser mode for the first time. As shown in Table 1, we simulate the transverse mode distribution without an e-block and with e-block thicknesses of 20 nm and 35 nm.

Our simulation focuses on maximizing the confinement of optical power from location 8.8 to 8.9 μm (MQW region) from the$x$-axis with a 4000-nm n-GaN buffer layer. This is the designed

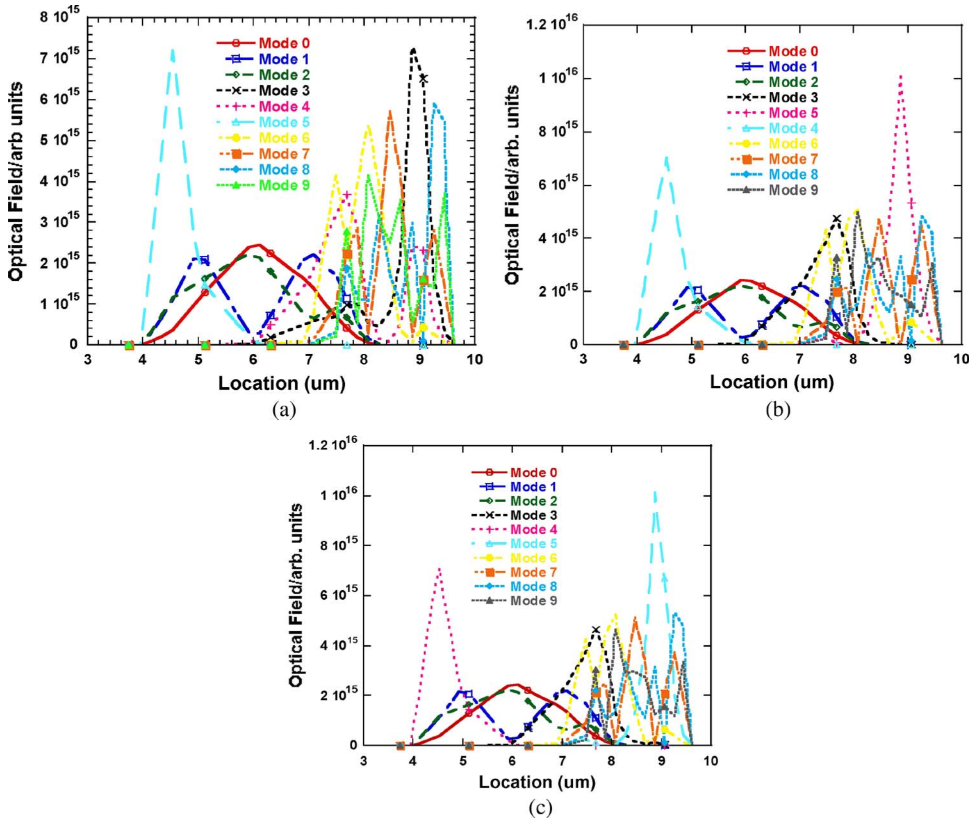

Fig. 1. Field intensities of each mode through the structure at 460-nm wavelength (a) no e-block, (b) an e-block with a 35-nm width, and (c) an e-block with a 20-nm width.

active region. We desire to design a lasing mode in the active layer instead of the substrate. The OCF of a chosen mode is defined as the ratio of the total guided energy of all the modes to the energy of the chosen mode located in the active region. The optical confinement of all the modes according to the design of Table 1 without an e-block is shown in Table 2, column 1, for a 460-nm wavelength. We see that the third mode is the lasing mode. Its OCF is 4.91%, which agrees with the results from [8]. The field intensity contribution from each mode is shown in Fig. 1(a) for this case. Although mode 3 has the highest field intensity in the MQW region, mode 5 has high field intensity in the substrate, as opposed to the active region. Modes found in regions outside the active region are called ghost modes [13], [14]. They are parasitic modes which occur due to the waveguide like properties of passive layers inside the structure. This ghost mode dissipates energy that could be used by the lasing mode and makes the laser less efficient. The optical confinement of all the modes in the design with an e-block of 35 nm width is also shown in Table 2. Table 2, Column 2, shows that mode 5 has the best OCF of 5.01% for this case, since the lasing mode should occur between 8.8 to 8.9 μm, as shown in Fig. 1(b). This mode has very few oscillations at 4.5 μm (substrate location). The optical confinement of all the modes in the design with an e-block of 20 nm width is shown in the Table 2 Column 3. From Table 2, we see that mode 5 also gives the highest OCF. It also gives the highest field intensity as shown in Fig. 1(c). Without the e-block, the substrate mode intensity (at location 4.5 μm) is almost equal to the lasing mode intensity (at location 8.8 to 8.9 μm), which is about 7×10^{15} a.u. as shown in Fig. 1(a). For the structure with the e-block [Fig. 1(b) and (c)], the lasing mode intensity is greatly enhanced ($\sim 10^{16}$ a.u.) and is much higher than the substrate/ghost mode. The e-block actually improves the optical mode in the laser cavity for this case. However, in general, the confinement factor of all modes varies when the e-block was removed. It is very clear that with the e-block, the lasing mode shifts to a higher order mode, and the OCF can be changed by about 14%.

TABLE 3
Optical confinement factors of each mode with $\lambda = 430$ nm

Mode	Optical Confinement Factor (%)		
	no e-block.	e-block of 35nm width	e-block of 20nm width.
(0,0)	0.000181236	3.47842e-005	5.37843e-005
(1,0)	0.00119628	0.000172161	0.000280763
(2,0)	0.00183944	0.000178779	0.000310567
(3,0)	6.48846	0.0116452	0.0314922
(4,0)	0.665776	1.4366e-005	6.22837e-005
(5,0)	6.81571e-005	5.46505	6.11234
(6,0)	0.110426	0.373773	0.219643
(7,0)	0.127324	0.135863	0.132975
(8,0)	0.707224	1.03036	0.888357
(9,0)	1.25963	1.49478	1.39863

TABLE 4
Optical confinement factors of each mode with $\lambda = 400$ nm

Mode	Optical Confinement Factor (%)		
	no e-block.	e-block of 35nm width	e-block of 20nm width.
(0,0)	0.000139042	1.94146e-005	3.13519e-005
(1,0)	0.00096935	9.43627e-005	0.000161123
(2,0)	0.00164004	9.66973e-005	0.000176117
(3,0)	7.61901	0.0059375	0.0170242
(4,0)	0.157396	7.38821e-006	3.08794e-005
(5,0)	3.31361e-005	6.02678	6.70086
(6,0)	0.0652654	0.283008	0.147521
(7,0)	0.134202	0.171566	0.155288
(8,0)	0.615611	0.924631	0.788146
(9,0)	1.17286	1.4475	1.33585

Wavelength dependence of OCF is also investigated. A total of nine cases are presented in which the thickness of the e-block width is varied among 0, 20, and 35 nm, and each of those cases is simulated with wavelengths of 400, 430, and 460 nm, as shown in Tables 2–4. The results show that for any e-block width, decreasing the wavelength will increase the lasing mode's OCF. The case with no e-block produces the highest OCF at 7.6% which was almost a full percent higher than our 20 nm e-block case for 400 nm. The e-block's contribution to OCF also varies with wavelength. They even have different trends for 460-, 430-, and 400-nm wavelength cases. For the 400-nm wavelength, the effectiveness of OCF improvement decreases with an increase of wavelength. Considering wavelength and e-block variation, with no e-block case, the OCF changed from 4.9% (460 nm) to 7.6% (400 nm), which is a 55% variation.

3.2. Bottom n-GaN Buffer Layer Design

To further reduce the substrate mode and study its effects, the bottom n-GaN buffer layer thickness is optimized between 0.1 and 7 μm. The goal is to find the width which creates the best OCF and the most coupling of different modes of propagation. The substrate width verses OCF of each mode from (0, 0) to (9, 0) are shown in Fig. 2. The design in [11] used a buffer layer width of 4 μm. Here, we study how the OCF varies according to a thinner GaN buffer. The n-GaN buffer thickness is an important parameter in the lasing-mode design. The maximum optical confinement

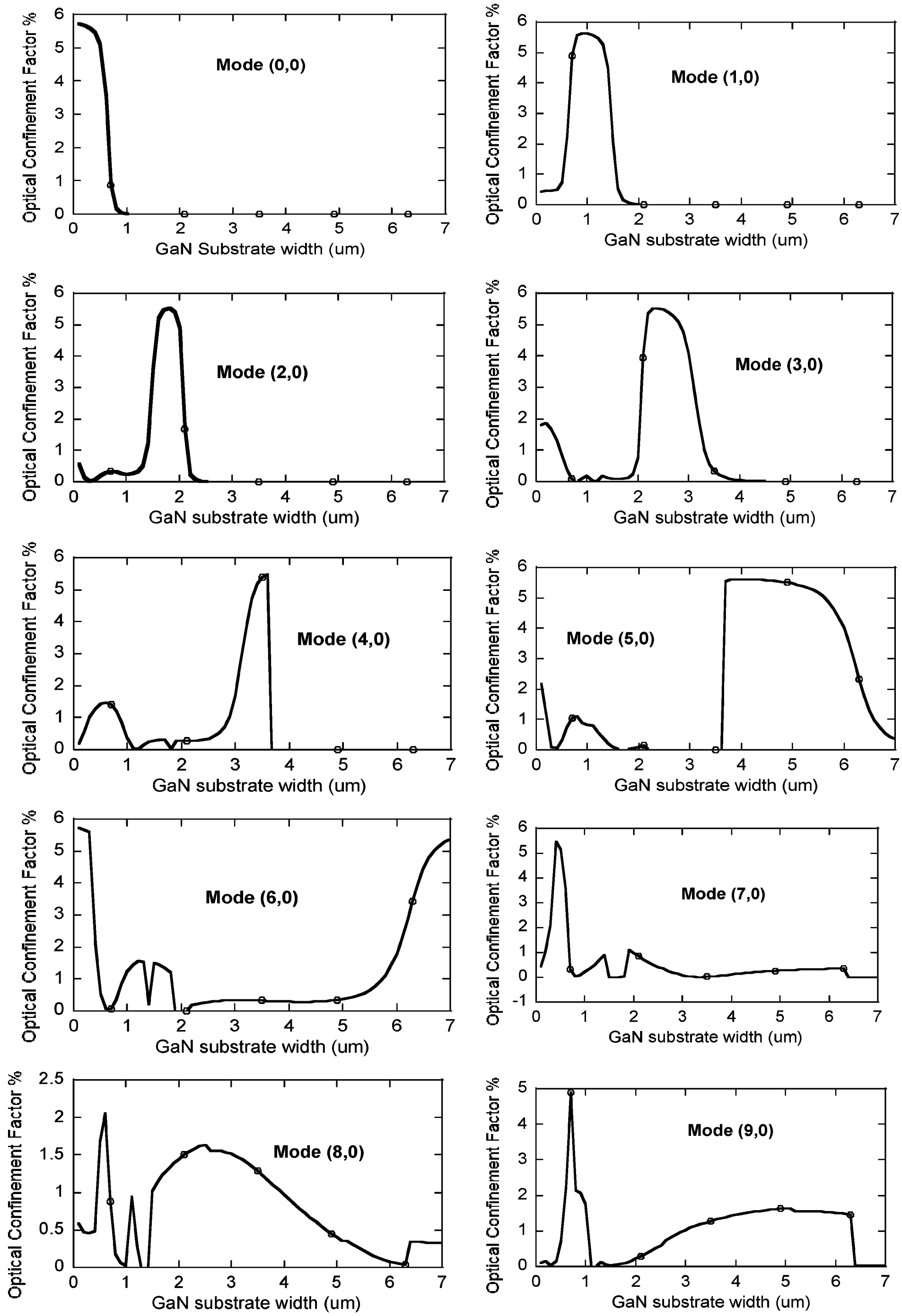

Fig. 2. Optical confinement factor variation of different optical mode versusGaN substrate thickness.

fact variation is due to transverse mode coupling. Also, the detailed order of the lasing mode is labeled at Fig. 2, which shows the mode order of the maximum OCF. Generally, starting with fundamental mode (0th), the lasing mode order increases with substrate thickness. In other words, the lasing mode is not represented by a single normal mode at different GaN substrate thickness but by a sequence of normal modes, with the mode order increasing by one at each subsequent transverse mode coupling. In general, the results show that the highest optical confinement is achieved with a substrate width of 0.1 μm, which also provides fundamental mode lasing condition. At this width, mode (0, 0) and mode (6, 0) both have an OCF of 5.7267%. Our simulation results show lower order lasing with a smaller substrate width. The nanosubstrate has the benefit of reducing the substrate mode, which lowers the threshold current since a wider layer increases the impedance of the diode. However, one factor that must be taken into account is the reason why we have a substrate/buffer layer. The buffer layer is added to reduce the number of defects or cracks in the layer of sapphire due to a lattice mismatch. To design an efficient GaN LD, we need to comprise between fabrication capability and theoretical optimization. Currently, new flip chip technology or nanolithography can be used for the thinner substrate to realize the optimized GaN LD performance [15], [16].

4. Conclusion

The effects of lasing wavelength and e-block layer thickness on the OCF are studied. The confinement factor of all modes dropped when the e-block was removed at 460 nm wavelength, and the e-block can improve the OCF of LD about 14%. With a 35-nm e-block, the lasing occurs with the third mode, and it has an OCF of 5.01%. The case with the 20-nm e-block has the best OCF of 5.61%, but when the wavelength reduces, the e-block reduces the confinement factor. The case with no e-block at a 400-nm wavelength produced the highest confinement factor at 7.61%, which is about a 55% variation compared with the 460-nm wavelength without e-block. The above simulation is all based on a substrate thickness of 4 μm. When the buffer layer is optimized with a 20-nm e-block, it is found that a thin buffer produced a better optical confinement of about 5.7267%. This is a small improvement from 5.61% (4-μm substrate) but is a step toward further optimization.

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