CHAPTER 2

OPTICAL FEEDBACK MECHANISM

The Conversion efficiency ($\eta$) is the ultimate parameter that determines the usefulness of a nonlinear frequency conversion system, the crucial endeavor always being to achieve a 100% conversion. We demonstrate here a simple configuration for both second harmonic generation (SHG) and sum frequency generation (SFG) that without focusing helps one to achieve a same value for $\eta$ as that obtained in a conventional setup but with much less input fundamental energy. In other words for same input energy now there will be a large enhancement in the value of $\eta$. Working on the principle of optical feedback, the fundamental advantages of the scheme are that neither does it require any focusing nor it demands any change in the energy of the primary laser source. Thus deployment of the new configuration will enable one to achieve a very high energy conversion with substantially lower input energy that is easily accessible and very much cost-effective than is presently required in a conventional setup. However, the scheme will be applicable for those interactions where input fundamental radiation itself is a secondary coherent source and not a primary laser. By primary source we mean coherent radiations coming out of an oscillator configuration, e.g., output from different standard lasers including dye laser as well as that from optical parametric oscillator (OPO). The coherent radiations obtained by extracavity frequency conversion including SHG of such primary sources in suitable nonlinear mediums are designated here as secondary coherent sources.

To demonstrate the feasibility of the new scheme in SHG process, the generation of 266 nm by SHG of 532 nm radiation is chosen as the latter can be a secondary coherent source when it is obtained through SHG of a primary laser (Nd: YAG) radiation. Moreover one of the aims of this work has been to study the development of high power sources at UV. Fourth harmonic (266 nm) of Nd: YAG laser radiation has many applications, such as processing of polymers and crystalline materials as well as in photolithography. In addition the scheme can be used to get tunable deep UV source as well by fourth harmonic of dye laser, in which the SHG of latter will be a tunable secondary source. One 14 mm long Type-I, $\theta = 68^0$ cut Lithium Tetraborate (Li$}_2$B$_4$O$_7$ or LB$_4$) crystal is available to us in which such generation of 266 nm by SHG can be realized with a phase-matching angle of 64.97$^0$ and hence it is used. To demonstrate the effectiveness of the scheme for SFG, we have chosen third harmonic
generation (THG) of Nd: YAG laser radiation in LB$_4$ where 355 nm is generated by SFG of 1064 nm and 532 nm radiations. Here 532 nm radiation is a secondary coherent source as it itself is generated by SHG of primary Nd: YAG laser radiation in a second nonlinear crystal like KD$_2$PO$_4$ (DKDP). The negative uniaxial crystal LB$_4$ although offers an extremely high laser damage threshold (about 40GW/cm$^2$ for 1064 nm radiation with pulse width of 1 ns), but its effective nonlinearity [1] is almost 6 times less than that of KDP. Thus conventional SHG or SFG yields quite low value for $\eta$, although we will presently show that $\eta$ can be significantly enhanced using our new scheme in either case.

2.1 Feedback Mechanism

Fig. 2.1 shows the experimental setup for feedback mechanism in case of SHG. The ordinary polarized 1064 nm ($\lambda_1$) radiation is obtained from an electro-optically Q-switched Nd: YAG laser (Spectra Physics, DCR-11) having pulse repetition rate of 10 Hz and pulse width of $\sim$ 10 ns. Its beam diameter is 5 mm. It is first allowed to pass through a 45° polarization rotator (R). The transmitted beam thus contains both ordinary (o) and extraordinary (e) polarizations. It is then frequency doubled by Type-II (eoe) interaction in a $\theta = 53°$ cut DKDP crystal to obtain the required secondary coherent source at 532 nm ($\lambda_2$). The DKDP crystal is rotated in a vertical plane. Thus $\lambda_2$ becomes ordinarily polarized. Both $\lambda_2$ and the unconverted part of $\lambda_1$ beam are next allowed to enter into the LB$_4$ crystal. Radiation at 266 nm ($\lambda_4$) is generated by Type-I (ooe) SHG of $\lambda_2$ in it. The unconverted part of $\lambda_1$ merely passes through LB$_4$ as the crystal cut does not allow any phase-matched interaction for it in the present position. A calcium fluoride ($\text{CaF}_2$) prism (P) separates $\lambda_4$ from $\lambda_2$ and $\lambda_1$. A $\text{CaF}_2$ lens (L) then weakly focuses $\lambda_4$ to keep the total beam within the active area of the sensor head of a power/energy meter (Gentec, ED100A) that measures its energy. This conventional set up for 266 nm generation, as we will show later, yields $\eta = 1.76\%$ with an input energy of 46 mJ at $\lambda_2$.

We now introduce four reflectors in the system to set up our proposed configuration. The dichoric mirror ($M_1$) transmits both $\lambda_4$ and $\lambda_1$ and reflects unconverted part of $\lambda_2$. The latter is denoted as $\lambda_{2F}$ and it is then further reflected by two right angle glass prisms ($G_1$ and $G_2$). Finally another dichoric mirror ($M_2$) having 99.8% reflectivity at $\lambda_2$ at 45° angle of incidence and 99.5% transmission for $\lambda_1$, reflects the former back into the system through point E on first surface of DKDP crystal as shown in Fig. 2.1. The available crystal cut for DKDP does
Fig. 2.1 Schematic diagram of the experimental setup for 266 nm generation in LB$_4$. R is a 45° rotator for 1064 nm; M$_1$ and M$_2$ are dichoric mirrors while G$_1$ and G$_2$ are glass prisms as mentioned in the text; Prism P and Lens L are both made of CaF$_2$; W is the beam dumper for 1064 nm radiation; S is the power/energy meter.
not allow any phase-matched interaction for 532 nm in its present position. Thus the latter
during its passage through DKDP suffers loss of energy only due to usual Fresnel's surface
reflection and minor absorption in the crystal. All these four reflectors are mounted on
standard optical mounts having provisions to execute both horizontal and vertical tilt motions
and they are positioned to form a rectangle. Moreover their positions with respect to each
other can be adjusted as per requirement. A careful alignment of all the components will now
provide the optical path ABCDEA as feedback track to track to $\lambda_2 F$. A positive feedback of
energy for $\lambda_2$ will now occur at E, the point from which the generation of $\lambda_2$ has started,
provided that the optical path-difference ($\Delta x$) and the phase-shift ($\Delta \phi$) between the original
and feedback part of the radiation satisfies the condition given by:

$$\Delta \phi = 2\pi (\Delta x / \lambda_2), \quad (2.1)$$

From Fig. 2.1 it can be seen that $\Delta x$ is equal to $AB + BC + CD + DE$, the segment EA being
traversed by both the beams in an identical manner. Equation (2.1) thus asserts that the
energy of the original 532 nm and that of its feedback residual will get added and intensity
becomes maximum if $\Delta \phi$ be an integral multiple of $2\pi$. The mounts of mirror $M_1$ and prism
$G_1$ are attached to each other so that they can be translated simultaneously maintaining a
parallel movement with respect to the other pairs. $\Delta \phi$ is optimized by changing $\Delta x$ with this
translation movement to ensure a positive feedback. One may utilize a three-reflector
arrangement as well for the purpose. However then both translation and rotation movements
of all three reflectors will be required to change $\Delta x$, which may not be quite easy. Although
one is free to choose any value of $\Delta x$ that simultaneously satisfies Equation (2.1) and is
suitable for positioning all the associated optical elements, for our convenience, we opt for $\Delta x$
= 106.4 cm. This makes $\Delta \phi = 4\pi \times 10^6$ radian and hence results in maximum intensity. With
proper alignment, as soon as Equation (2.1) is satisfied, a large enhancement in energy of $\lambda_4$
is observed from the power/energy meter reading.

Figure 2.2 shows the experimental setup for feedback mechanism in case of SFG. The
required secondary coherent source of 532 nm ($\lambda_2$) using the fundamental radiation 1064 nm
($\lambda_1$) is obtained by the same process as stated earlier. The THG is done in a 20 mm long $\theta =
32^\circ$ cut LB$_4$ crystal (X2) by Type-I interaction. Thus only the 'o' polarized part of the
residual $\lambda_1$ has contribution in the THG. But as the damage threshold of X2 is very much
above the used intensity levels hence no attempt is made to separate the unused 'e' part of $\lambda_1$.
However, this can be easily done by placing a Glan at point K, which will introduce a minor
Fig. 2.2 Schematic diagram of the experimental setup for 355 nm generation in LB₄ (X2). R is a 45° rotator for 1064 nm; M₁ and M₂ are dichoric mirrors. Prism P and Lens L are both made of CaF₂ while G₁ and G₂ are glass prisms as mentioned in the text; W is the beam dumper for 1064 nm radiation; S is the power/energy meter.
loss in the system. Thus after SHG in X1, the total residual part of $\lambda_1$ and the generated $\lambda_2$ radiations are allowed to enter collinearly in X2 for THG. The experimentally obtained value of phase-matching angle ($\theta$) for THG agrees quite satisfactorily with the theoretically predicted value of 40.23° using reported Sellmeier coefficients [2] for LB4. For Type-I interaction, the value of the effective nonlinearity ($d_{\text{eff}}$) for LB4 is given by $d_{31} \sin \theta$, where $d_{31}$ is 0.15 pm/V [1]. Hence for this THG interaction the value of $d_{\text{eff}} = 0.097$ pm/V. A prism (PR1) made from calcium fluoride (CaF2) separates $\lambda_3$ from $\lambda_2$ and $\lambda_1$. A CaF2 lens (L) then loosely focuses $\lambda_3$ to keep the total beam within the area of the sensor head (S) of a power/energy meter (Gentec, ED100A) that measures its energy. Thus LA, R, X1, X2, PR1, L and S in Fig. 2.2 constitute what is usually meant as a conventional setup for THG. It will be seen later that such a conventional set up yields $\eta = 6.5\%$ under present condition when the measured input energies are 140 mJ ($E_1$) at 1064 nm (energy of ‘o’ part only) and 46 mJ ($E_2$) at 532 nm. The corresponding intensities are respectively 71 and 23.4 MW/cm². The measured energy ($E_3$) of the generated 355 nm is 5.2 mJ.

The aim is now to increase the energy of $\lambda_2$ not by increasing the energy of $\lambda_1$ but by utilizing energy of residual part of $\lambda_2$, denoted henceforth as $\lambda_{2F}$, after THG in X2. This is because any increase in $E_2$ will increase $E_3$. For this purpose, $\lambda_{2F}$ is feedback in exactly same way as in case of SHG using mirror/Prism combinations as shown in Fig. 2.2. However in this case, the dichoric mirror M1 placed at point A transmits both $\lambda_3$ and $\lambda_1$ and reflects $\lambda_{2F}$. The other optical components remain unchanged. Again a careful alignment of all the optical components will now provide optical feedback path for $\lambda_{2F}$ along ABCDEA. The energy ($E_{2F}$) of $\lambda_{2F}$ will get added to $E_2$ of the original beam at E, the point from which the generation of $\lambda_2$ has started provided Equation (2.1) is satisfied. As $\Delta \phi$ depends on $\lambda_2$ and as it has not been changed, hence chosen value of $\Delta \phi$ remained same (106.4 cm). With proper alignment there is a good enhancement in energy of $\lambda_3$ as is evident from the power/energy meter reading.

The generation with our employed feedback system remains quite stable either for SHG or for SFG and no noticeable change in performance is observed owing to possible small fluctuations of air temperature or similar minor disturbances that may arise in laboratory environment.
2.2 Enhancement in Second Harmonic Generation

For the theoretical prediction of the generated energy \( E_4 \) at \( \lambda_4 \) from a given fundamental input energy \( E_2 \) at \( \lambda_2 \) we use the well-known relation [3]:

\[
E_4 = E_2 \tanh^2 \left( \frac{8\pi^2 d_{22}^2 \ell^2 I_2}{e_0 c n_2^0 n_4^0 \lambda_2^2} \right)^{1/2}
\]

(2.2)

The subscripts "2" and "4" in Equation (2.2) represent 532 and 266 nm radiations respectively. Crystal length \( l \), wavelength \( \lambda_2 \) and the beam radius \( r \) are in meter. \( E \)'s are energies in mJ. \( P \)'s are the peak powers in Watt and \( I \)'s are intensities (\( P/\pi r^2 \)) in Watt/m\(^2\) associated with \( E \)'s for different interacting beams. For the present interaction, the effective nonlinearity \( (d_{\text{eff}}) \) of LB\(_4\) in SI unit is 0.14 pm/N. Transmission characteristic of the used LB\(_4\) crystal as measured by a spectrophotometer (Hitachi, U-3400) has ensured a 90% transmission for both \( \lambda_2 \) and \( \lambda_4 \), which on calculations give the values of the absorption coefficients respectively as \( \alpha_2 = 0.00215 \) cm\(^{-1}\) and \( \alpha_4 = 0.00973 \) cm\(^{-1}\). Thus the effect of absorption in the used LB\(_4\) is not very high and can be neglected for practical purpose. \( n \)'s are the refractive indices calculated by using reported [2] Sellmeier coefficients.

For Type-II SHG in DKDP with an input energy \( (E_1) \) of 272 mJ \( (I_1 = 139 \text{ MW/cm}^2) \) at \( \lambda_1 \), the measured value of \( E_2 \) is 46 mJ \( (I_2 = 23 \text{ MW/cm}^2) \) and results are summarized in Table 2.1. The latter becomes the input fundamental energy for subsequent SHG in LB\(_4\). First, \( E_4 \) is measured without placing the mirror \( M_1 \) i.e. without feedback and it is found to be 810 \mu J. Thus \( \eta = 100 \times 0.810/46 = 1.76\% \) as indicated earlier. For such low value of \( \eta \), pump depletion is negligibly small and hence approximately 45 mJ \( (E_2-E_4) \) of energy should remain available with unconverted 532 nm for feedback. Now positioning the mirror \( M_1 \) and making necessary alignments the feedback is achieved. However, we should mention that the feedback radiation suffers energy losses of about (i) 8% at \( M_1 \) as the used mirror has a reflectivity of 92% only for \( \lambda_2 \), (ii) \( \sim 10\% \) (surface reflection loss) at each of the two uncoated glass prisms used in absence of two mirrors with appropriate coatings for \( \lambda_2 \) and (iii) another \( \sim 10\% \) due to transmission through DKDP. Considering such losses, the total loss factor amounts to \( [1- 0.92x0.9x0.9x0.998x0.9] = 0.33 \) i.e. 33%. Hence the feedback energy \( (E_{2F}) \) should be \((46-0.81) \times 0.67 = 30 \) mJ. With feedback, the measurement of energy of \( \lambda_2 \) at point K in between DKDP and LB\(_4\), after properly separating it from 1064 nm, shows a value of 74 mJ. Thus \( E_{2F} \) is 74-46 = 28 mJ that is in good agreement with its estimated value. Obviously, during this measurement, the LB\(_4\) crystal is kept in non-phasematched
position for SHG. A better agreement can be obtained if absorption of $\lambda_2$ in LB$_4$ and loss due to surface reflections are considered. We will denote this feedback-enhanced energy of $\lambda_2$ by $E_2'$. The measured value of $E_4$ with this feedback becomes 1.86 mJ. This makes $\eta = 2.5\%$ with respect to input $E_2'$. But it must be noted that $E_2$ is increased to $E_2'$ not by increasing $E_1$, the energy of primary laser radiation (1064 nm), but by utilizing the unconverted part of $E_2$ itself. Thus the actual conversion efficiency is 4\% (100x1.86/46), which is 2.3 times (1.86/0.81) enhancement over SHG without feedback. Experimental results are summarized in Table 2.2. It must be pointed out that if mirrors with appropriate coatings be used so that all of them have 99.8\% reflectivity for $\lambda_2$, then the feedback radiation would suffer a loss of $[1 - 0.998 \times 0.998 \times 0.998 \times 0.998 \times 0.9] = 0.11$ or 11\%. Then $(46 - 0.81) \times 0.89 = 40$ mJ of unconverted energy at 532 nm can be used as feedback and the calculation shows that the obtained enhancement factor of 2.3 will still increase to as high as 4.1 in this given experimental setup. The value of $\eta$ will then be 7.2\%, which is a large enhancement as compared to 1.76\% obtained with the conventional SHG process. Moreover, it is realized without focusing and without making any change in the energy of the primary laser source (Nd: YAG).

A higher energy than 46 mJ at 532 nm is not possible presently from our system without focusing. Hence, we present the case of high conversion efficiency through theoretical analysis extending it for very high input energy. For this analysis, we assume a loss of 11\% for the feedback as has been accounted for just before. Thus for each value of $E_2$ and its corresponding $E_4$, the feedback energy ($E_{2F}$) can be given as $E_{2F} = (E_2 - E_4) \times 0.89$. First for a given $E_2$, corresponding value of $E_4$ and hence $\eta$ without any feedback is calculated by Equation (2.1). Curve 1 in Fig. 2.3 shows the variation of $\eta$ with $E_2$. The same calculation is again done with input $E_2' (= E_2 + E_{2F})$ as obtained with feedback. Curve 2 in the same figure depicts the variation of $\eta$ with this modified value of $E_2$. It is seen that to achieve the same value of $\eta$ one needs almost four times less input energy by employing the new feedback configuration. For example, an input energy as high as 2 J ($I_2 = 1000$ MW/cm$^2$) will be required in the present setup to obtain $\eta = 55\%$ without implementing feedback while its deployment drastically reduces the energy requirement down to 530 mJ ($I_2 = 270$ MW/cm$^2$). Energy requirements are substantially high due to very low nonlinearity of LB$_4$.

Focusing is of course considered to be an effective method to increase $\eta$ for a given input energy. It can be judiciously employed with the new scheme to achieve higher conversion with
Table 2.1
Energy of 532 nm generated by DKDP crystal at the point K in Fig. 2.1 & Fig. 2.2

<table>
<thead>
<tr>
<th>Input energy of 1064 nm at the point E in mJ</th>
<th>Output energy of 532 nm at the point K (E₂) in mJ</th>
<th>Conversion Efficiency η=E₂ x100/√(E₁° x E₁°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E₁°</td>
<td>E₁°</td>
<td>Theo</td>
</tr>
<tr>
<td>163</td>
<td>109</td>
<td>53</td>
</tr>
</tbody>
</table>

Table 2.2
Energy of 266 nm generated in LB₄ crystal at the point A in Fig. 2.1

<table>
<thead>
<tr>
<th>CONFIG.</th>
<th>Input energy of 532 nm at the point K (E₂) in mJ</th>
<th>Feedback energy of 532 nm at the point E (E₂F) in mJ</th>
<th>Total energy of 532 nm at the point E (E₂=E₂+E₂F) in mJ</th>
<th>Output energy of 266 nm at the point A (E₄) in mJ</th>
<th>Conversion Efficiency η=[E₄/E₂] X 100</th>
<th>Enhancement Ratio N=([η]WF/[η]WOF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Feedback i.e. Mirror M₁ is absent (WOF)</td>
<td>46</td>
<td>0</td>
<td>46</td>
<td>0.94</td>
<td>0.81</td>
<td>2.04</td>
</tr>
<tr>
<td>With Feedback i.e. Mirror M₁ is present (WF)</td>
<td>46</td>
<td>28</td>
<td>74</td>
<td>2.45</td>
<td>1.86</td>
<td>5.33</td>
</tr>
</tbody>
</table>
Fig. 2.3 Theoretical Variation of conversion efficiency ($\eta$) for generation of 266 nm by SHG in LB$_4$ with input energy ($E_2$) of fundamental radiation without (curve 1) feedback, with (curve 2) feedback and with both focusing and feedback (curve 3) as discussed in text.
Fig. 2.4 Experimental setup for 266 nm generation in LB$_4$ incorporating focusing effect and three-reflector feedback arrangement. L$_1$ and L$_2$ are the convex-concave mirror combination; M$_3$ is a dichoric mirror for 532 nm radiation. L in Fig. 2.1 is designated here as L$_3$, all the other components being same as in Fig. 2.1.
still lower value of input energy. The focusing should be done for the primary laser radiation (1064 nm in our experiment) before mirror M₂ using a pair of convex-concave lenses of appropriate focal lengths and with proper separation in between them. This is needed to restrict the beam divergence such that the focused spot size does not change appreciably within a distance that is very much greater than the length of the optical path EABCDE. This will ensure proper interaction in between the original and feedback beams of λ₂. Fig. 2.4 shows a potential setup incorporating both focusing and three-mirror feedback combination discussed earlier. Obviously the limit of focusing will depend not only on the laser damage threshold of the used nonlinear crystals, but also on those of the different optical components and their coatings. Curve 3 in Fig. 2.3 shows the effect of focusing when incorporated in the new scheme in the way mentioned above. The amount of focusing is considered to reduce the original 5 mm spot size to 3 mm. It is evident from Curve 3 that to achieve η = 55%, instead of 530 mJ with feedback configuration, one now needs only 190 mJ (270 MW/cm²). All the required optical components that can withstand intensity much greater than 270 MW/cm² at 532 nm are commercially available and hence the scheme is quite attractive from device point of view and it is cost-effective as well.

Thus a simple feedback scheme can be successfully incorporated for large enhancement of SHG with secondary coherent source without focusing or making any change in the energy of the primary laser.

2.3 Enhancement in Sum Frequency Generation

Incorporation of a new optical feedback mechanism in a conventional setup considerably enhances the conversion efficiency (η) of sum-frequency generation (SFG) also in a nonlinear crystal as compared to conventional scheme without it.

In SFG with input wavelengths λ₁ and λ₂ generating the sum-frequency wavelength λ₃, where λ₁>λ₂>λ₃, the conversion efficiency is usually defined as,

\[ \eta = \frac{100E_3}{\sqrt{E_1E_2}} \]  

(2.3)

where E₁'s are the respective energies of λ₁’s. It is thus obvious that with fixed spot sizes of input laser beams, η in a nonlinear crystal of a given length increases with the increase of either E₁ or E₂ or both.

Using plane-wave approximation, the theoretical prediction for E₃ in X₂ from given values of E₁ and E₂ has been made by using the well-known relation [4]:
\[
E_2 = \left( \frac{\lambda_2}{\lambda_3} \right) E_1 \tanh^2 \left[ \frac{8\pi^2 \ell^2 d_{\text{eff}}^2 T_1 T_2 F P_1}{\varepsilon_0 n_1^2 n_2^2 n_3^2(\theta) \lambda_2 \lambda_3 \pi^2} \right]^{1/2}
\]

where
\[
F = \{ -1 + 2 \exp(-\alpha'/2) + \exp(-\alpha') \}/(\alpha'/2)^2 \exp(-\alpha_3 l)
\]
\[
\alpha' = (\alpha_1 + \alpha_2 - \alpha_3)/l
\]

In Equation (2.4) all the parameters have same meaning as specified in Equation (2.2). Transmission characteristics of X2 as measured by a spectrophotometer (Hitachi, U-3400) had confirmed 91.1%, 94.7% and 93.2% transmissions respectively at \(\lambda_1\), \(\lambda_2\) and \(\lambda_3\) for this 20 mm long LB4 sample. The absorption coefficients of respective beams by using these values come out to be \(\alpha_1 = 0.004\) cm\(^{-1}\), \(\alpha_2 = 0.0025\) cm\(^{-1}\) and \(\alpha_3 = 0.02\) cm\(^{-1}\). The factor F is in m\(^{-1}\) that takes into account the effect of absorption of the interacting radiations [4] in X2 and hence includes \(\alpha_1\), \(\alpha_2\) and \(\alpha_3\). Subsequent calculation gives the value of F as 95 for the used sample. T’s are the percent transmission of the first surface of X2 that the interacting beams encounter. \(P_1\) is the peak power in Watts for \(\lambda_1\).

The results for generation of 532 nm by Type-II SHG in X1 have already been summarized in Table 2.1. We then measure the energy of the ‘o’ part of the residual part of \(\lambda_1\) as only this fraction takes part in the subsequent THG in LB4 and this is what we denote as \(E_1\) now. The measurement is done after two polarized parts of the residual beam are separated by a Glan prism. The measured value is 140 mJ. Then \(E_3\) is measured without placing the mirror \(M_1\) i.e. without feedback and it is found to be 5.2 mJ. Thus \(\eta = 6.5\%\) using Equation (2.3) as indicated earlier. Now positioning the mirror \(M_1\) and \(M_2\) along with \(G_1\) and \(G_2\) and making necessary alignments the feedback is achieved. Since value of \(\eta\) in X2 without feedback is appreciably low, there is almost no noticeable depletion of either \(E_1\) or \(E_2\). Hence substantial amount of energy, \(E_2F\), should thus remain available for feedback. However, \(M_1\) has a reflectivity of 92% only for \(\lambda_2\). Also since we have used two uncoated glass prisms, some amount of losses have crept in the feedback radiation. Moreover it suffers some more loss when passing through X1. The total energy of \(\lambda_2\) with feedback as measured at point K in between X1 and X2 is 78 mJ. Since \(E_2\) is 46 mJ, hence the value of \(E_2F\) is 32 mJ. From this we can estimate an approximate loss factor 100x\((E_2-E_2F)/E_2\) = 30\% in feedback radiation which includes the loss in the value of \(E_2\) in generating the THG, although the latter contributes only marginally to this total loss factor owing to low conversion. The major loss has been incurred owing to surface reflections at different optics and crystals. We will denote
this feedback-enhanced energy of $\lambda_2$ by $E_{2T}$ i.e. $E_{2T} = 78$ mJ. The measured value of $E_3$ with this feedback becomes 7.84 mJ. This makes $\eta = 7.5\%$ with respect to input energies $E_1$ and $E_{2T}$. But it must be noted that $E_2$ is increased to $E_{2T}$ not by increasing $E_{1F}$, the energy of primary fundamental laser radiation, but by utilizing $E_{2T}$. Thus the actual overall conversion efficiency is 9.8% [100x7.84/(140x46)] $\%$, which is a noticeable enhancement over THG efficiency of 6.5% without feedback. We define the enhancement factor (N) as the ratio of values of $\eta$ obtained with feedback ($\eta_{WF}$) and without feedback ($\eta_{WOF}$). Thus in our case the value of N is 1.5 (= 9.8/6.5). Experimental results are summarized in Table 2.3. It must be pointed out that if mirrors with appropriate coatings be used so that all of them have 99.8% reflectivity for $\lambda_2$, then the feedback radiation would suffer a loss of $[1 - 0.998x0.998x0.998x0.998x0.947] = 0.06$ or 6%. Then $(46-5.2) \times 0.94 = 38$ mJ of unconverted energy at 532 nm can be used as feedback ($E_{2F}$). $E_{2T}$ will then be 84 mJ and the subsequent calculations show that the value of N will increase to 2.2 from 1.5 in this given experimental setup. The value of $\eta$ will then be 14.3%, which is a large enhancement as compared to 6.48% obtained with the conventional THG process. Moreover, it is realized without focusing and without making any change in the energy of the primary laser source (Nd: YAG).

As in case of SHG, we present the case of high conversion efficiency through theoretical analysis extending it for very high input energy. With the increase of energy ($E_1$) of 1064 nm energy ($E_2$) of SHG beam generated at crystal X1 (in Fig. 2.2) also increases according to Equation (2.2). 1064 nm beam after passing through the 45° rotator (R), we get 60% o-polarized beam and rest 40% corresponds to e-polarization. So, at the point K residual part of o-polarization, which is used for THG in crystal X2, is given by $(E_1 - E_2) \times 0.6$. For this analysis, we assume a loss of 6% for the feedback as has been accounted for just before. Thus for each value of $E_2$ and its corresponding $E_3$, the feedback energy ($E_{2F}$) can be given as $E_{2F} = (E_2 - E_3) \times 0.94$. First for a given $E_2$, corresponding value of $E_3$ and hence $\eta$ without any feedback is calculated by Equation (2.4). Curve 1 in Fig. 2.5 shows the variation of $\eta$ with $E_2$. The same calculation is again done with input $E_{2T}$ (= $E_2 + E_{2F}$) as obtained with feedback. Curve 2 in the same figure depicts the variation of $\eta$ with this modified value of $E_2$. It is seen that to attain the same value of $\eta$ one needs almost two times less input energy by employing the new feedback configuration.

For comparison, we have also conducted the same experiment with a 10 mm thick, 53° cut DKDP [5] crystal. It is placed at position X2 instead of LB4 without changing any other components depicted in Fig 2.2. However since $d_{eff}$ of DKDP is higher for Type-II interaction
Table 2.3

Experimental results of THG in LB₄ crystal at the point A in Fig. 2.2 with and without using optical feedback mechanism

<table>
<thead>
<tr>
<th>CONFIG.</th>
<th>Input Energy of 1064 nm at the point D (E₁) in mJ</th>
<th>Input energy of 532 nm at the point K (E₂) in mJ</th>
<th>Feedback energy of 532 nm at the point E (E₂F) in mJ</th>
<th>Total energy of 532 nm at the point E E₂T = E₂+E₂F in mJ</th>
<th>Output energy of 355 nm at the point A (E₃) in mJ</th>
<th>Conversion Efficiency η = [E₃/√E₁E₂] X 100</th>
<th>Enhancement Ratio N = η₁WF/η₁WOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Feedback i.e. Mirror M₁ is absent (WOF)</td>
<td>140</td>
<td>46</td>
<td>0</td>
<td>46</td>
<td>6.3</td>
<td>5.2</td>
<td>7.85</td>
</tr>
<tr>
<td>With Feedback i.e. Mirror M₁ is present (WF)</td>
<td>140</td>
<td>46</td>
<td>32</td>
<td>78</td>
<td>11</td>
<td>7.84</td>
<td>13.7</td>
</tr>
</tbody>
</table>
Fig. 2.5 Theoretical Variation of conversion efficiency ($\eta$) for generation of 355 nm by SFG in LB$_4$ with input energy ($E_2$) of fundamental radiation without (curve 1) feedback, with (curve 2) feedback.

Fig. 2.6 Theoretical Variation of conversion efficiency ($\eta$) for generation of 355 nm by SFG in DKDP with input energy ($E_2$) of fundamental radiation without (curve 1) feedback, with (curve 2) feedback.
Table 2.4

Energy of 532 nm generated by DKDP crystal at the point K in Fig. 2.2

<table>
<thead>
<tr>
<th>Input energy of 1064nm at the point E in mJ</th>
<th>Output energy of 532 nm at the point K (E2) in mJ</th>
<th>Conversion Efficiency ((\eta = \frac{E_2 \times 100}{\sqrt{E_1^0 \times E_1^0}}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1°</td>
<td>E1°</td>
<td>Theo</td>
</tr>
<tr>
<td>25</td>
<td>13</td>
<td>4.3 3.8 24.41 21.07</td>
</tr>
</tbody>
</table>

Table 2.5

Experimental results of THG in DKDP crystal at the point A in Fig. 2.2 with and without using optical feedback mechanism

<table>
<thead>
<tr>
<th>CONFIG.</th>
<th>Input Energy of 1064nm at the point D (E1) in mJ</th>
<th>Input energy of 532nm at the point K (E2') in mJ</th>
<th>Feedback energy of 532 nm at the point E (E2) in mJ</th>
<th>Total energy of 532 nm at the point E E2T = E2+E2F in mJ</th>
<th>Output energy of 355 nm at the point A (E3) in mJ</th>
<th>Conversion Efficiency (\eta = \frac{E_3}{\sqrt{E_1 E_2}}) X 100</th>
<th>Enhancement Ratio (\frac{N}{\eta_{WF}/\eta_{WOF}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Feedback i.e. Mirror M1 is absent (WOF)</td>
<td>87 46 0 46 15.1 13.8 23.9 21.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With Feedback i.e. Mirror M1 is present (WF)</td>
<td>87 46 26 72 24.0 19.1 37.9 31.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
as compared to Type-I, hence Type-IIA (eoe) interaction is employed. So, after SHG in the crystal X1, the ‘e’ polarized part of unconverted fundamental 1064 nm radiation is allowed to enter collinearly in DKDP (which is now crystal X2) for THG along with generated SHG since only this fraction will contributed in THG. The measured transmissions of the used DKDP respectively at λ₁, λ₂ and λ₃ are 85%, 84% and 80%, which amounts to absorption coefficients of α₁ = 0.087 cm⁻¹, α₂ = 0.095 cm⁻¹ and α₃ = 0.14 cm⁻¹. Thus F = 0.85 cm⁻¹ and its energy is given by \((E₁-E₂)x0.4\) and the measured energy for this part is 87 mJ. Experimental results obtained in this case are listed in Table 2.5. It is obvious that since the factor \(l_{\text{eff}}\) of DKDP is higher than that of LB₄, hence generation of THG will also be higher without feedback in the former and thus less energy will remain available for feedback. Here we find the actual conversion efficiency is 30.98%, which is 1.42 times (i.e. 21.81%) enhancement over THG without feedback. The theoretical variation of conversion efficiency considering a loss of 6% for the feedback is shown in Fig. 2.6. The calculation is same as previous. Curve 1 and 2 in the figure depicts the variation of \(\eta\) respectively with the regular \(E₂\) and its modified value. It is seen that to achieve the same value of \(\eta\) one needs almost two times less input energy by employing the new feedback configuration.

Thus a simple feedback scheme can be successfully employed for SFG with secondary coherent source that significantly enhances its conversion efficiency. There are numerous such SFG interactions, namely, fifth harmonic generation of Nd: YAG laser radiation, THG of Dye laser and CO₂ laser radiations, deep UV generation by SFG etc, where one of the input radiations is a secondary coherent source. The demonstrated feedback scheme can be effectively applied for considerable enhancement of conversion efficiency in all such interactions.

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References


